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U S ARMY NATICK LABORATORIES

TECHNICAL REPORT

ES-8

A STUDY OF WINDBORNE SAND AND DUST IN DESERT AREAS

EARTH SCIENCES DIVISION

AUGUST 1963

NATICK, MASSACHUSETTS

U. S. ARMY NATICK LABORATORIES

Natick, Massachusetts

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Technical Report
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A STUDY OF WINDBORNE SAND AND DUST IN DESERT AREAS

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Project Reference:
7X83-01-008

August 1963

FOREWORD

Certain problems arise in connection with Army activities in desert areas; these problems are quite different from those encountered in more humid parts of the world. These include encroachment by moving bodies of sand on fixed installations and deterioration of equipment through the abrasive action of windborne sand and dust.

That such problems exist is well known, but the natural requirements for actuating sediment transport by the wind have not been definitely established. If rules could be developed to permit the prediction of equipment damage by wind-carried materials, such predictions would have considerable value from the military point of view in the analysis of desert environments. With this in mind, a contract to investigate the mechanics of aeolian transportation of dust and sand was negotiated with the University of Southern California. Dr. Thomas Clements, Head, Department of Geology, was the principal investigator. This report is a product of that contract. It features those sections of the contract study dealing with threshold velocities for particle movement at the surface and the vertical distribution of sand and dust during transport. The material presented remains essentially as submitted except for minor editorial changes and the redrafting of all maps and graphs.

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ABSTRACT

Severe sand and dust storms occur at a rate of less than 2 per year on the average in the desert areas of southwestern United States. Less severe storms average about 4 per year. Most storms occur in late winter or spring and last for a period of 1 to 3 days. Storm incidence is higher in desert areas that have been disturbed by man's activities, such as agriculture or large-scale military maneuvers. During a storm, sand and dust in militarily significant amounts are carried a few miles at most, but generally only a few hundreds or thousands of feet. Wind-driven sand is carried mostly within 2 feet of the ground, with 6 feet as a maximum height in all but extremely high winds.

Critical pick-up velocities of winds vary according to the type of desert surface, the grain size and coherency of the surface materials, and whether or not the surface has been disturbed artificially. In dune areas, winds of 10 to 15 miles per hour will initiate movement, and on other sandy terrain, winds of 20 miles per hour will be necessary for this. Fine materials on desert flats will be set in motion at 20 to 25 miles per hour, and on alluvial fans and playas at 30 to 35 miles per hour. No wind-blown material will be derived from desert pavements unless the surface has been broken, and on all other above-mentioned types, disturbing the surface will lower critical pick-up velocities by as much as 5 miles per hour.

A STUDY OF WINDBORNE SAND AND DUST IN DESERT AREAS

SECTION I. A GENERAL ANALYSIS OF SAND AND DUST STORM CHARACTERISTICS

1. Causes of dust storms in the deserts of southwestern United States

Sand and dust storms in the deserts of southwestern United States result from winds of relatively high velocity, generally in excess of 35 miles per hour. However, before considering the specific causes for winds in this velocity range, it is worthwhile to first examine the general wind-flow pattern over the southwestern portion of the United States.

A generalized picture of atmospheric pressure and prevailing winds is shown in Figure 1, an adaptation of the work of Ives (1941). The most significant features of the map are: the belt of westerly winds that lies to the north of the desert area, the cold current that flows southward along the California coast, the area of high pressure over the Pacific Ocean, and the area of low pressure located to the south of the deserts under consideration, centering in the Sonoran Desert of Mexico. During the course of a year, the Pacific High moves through about 16 degrees of latitude. In summer it is centered at 40 degrees north latitude, and in winter at about 24 degrees north latitude. Throughout the winter months a sharp pressure contrast exists between a cell of high pressure that has developed over the Great Basin and the Sonoran low-pressure system to the south which has become centralized in the area to the southwest of Yuma, Arizona. In spring and autumn the Sonoran Low breaks up into several weak lows which are centered over the larger desert basin (Ives, 1941, p 173). It is from the interplay of these basic pressure systems that strong winds are produced in the deserts of California.

a. Storms from the west

The most common situation producing strong desert winds exists in late winter and spring when the Pacific High is near its southernmost position and when a deep low-pressure cell is centered in the Great Basin in the general vicinity of Tonopah, Nevada. This situation produces a pressure gradient from west to east and results in strong winds blowing from the westerly quadrant, usually as southwest or southeast winds. Conditions similar to these, as shown in Figures 2 and 3, produced intense dust storms on 11 March 1950 and 27 December 1953.

During the windstorm of 11 March 1950, winds reached a reported velocity of 85 miles per hour at Daggett, 65 miles per hour at Mojave, and 60 miles per hour at Palmdale. At times during the storm, swirling sand reduced visibility to 10 feet and dust filled the atmosphere. Wind-driven

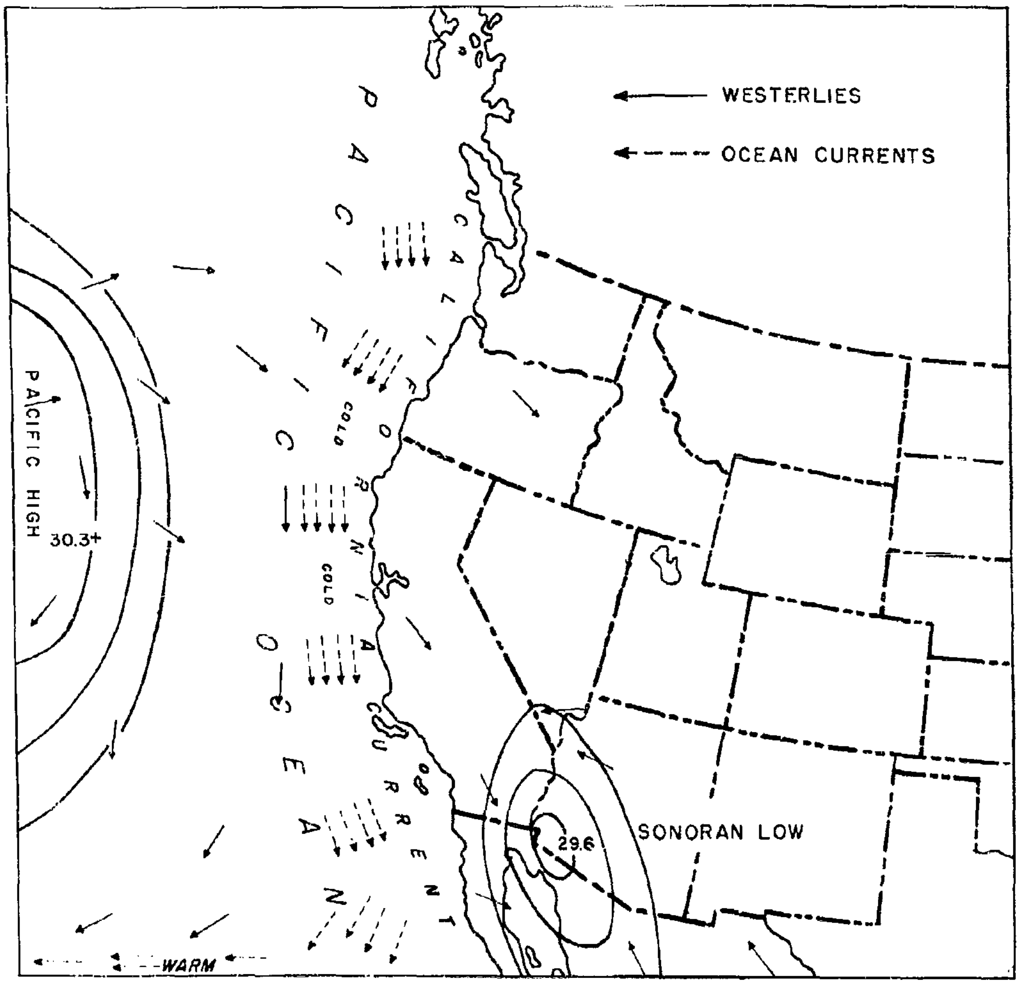

Figure . Generalized pressure, wind, and ocean current map of western United States.

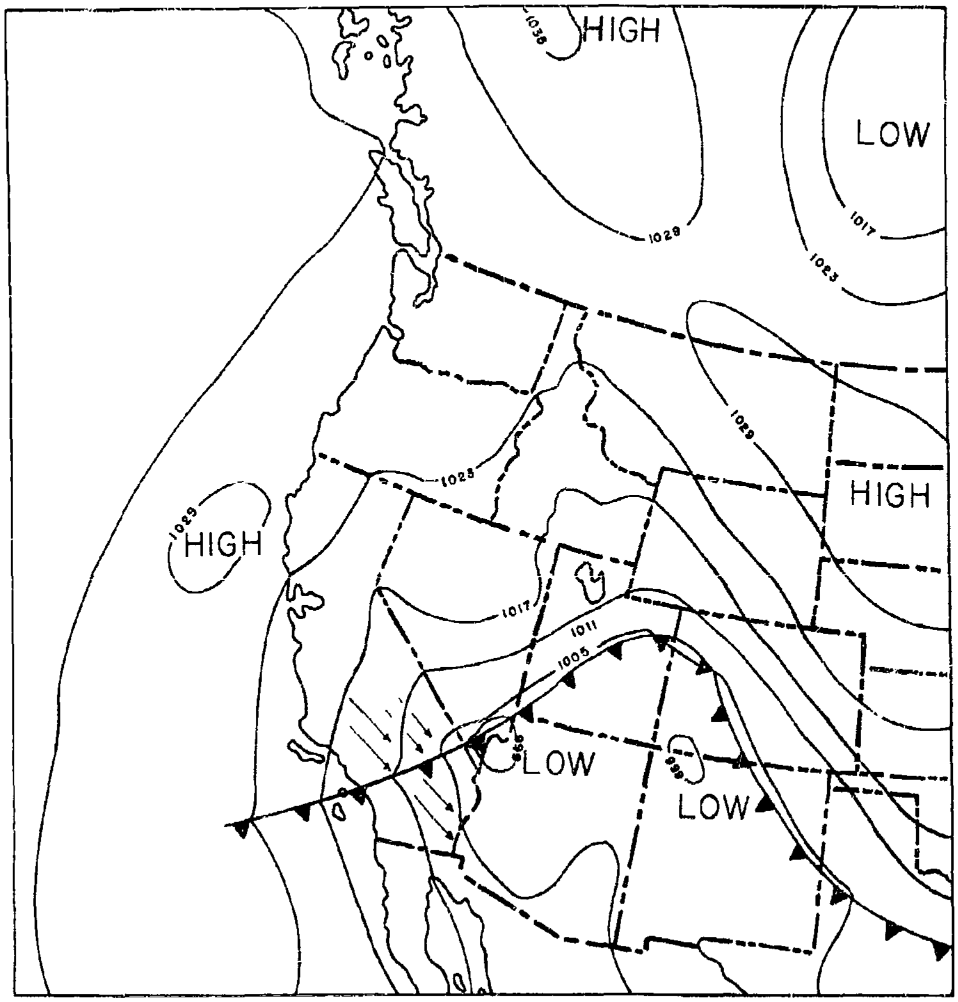

Figure 2. Weather conditions producing sand storm of 11 March 1950.

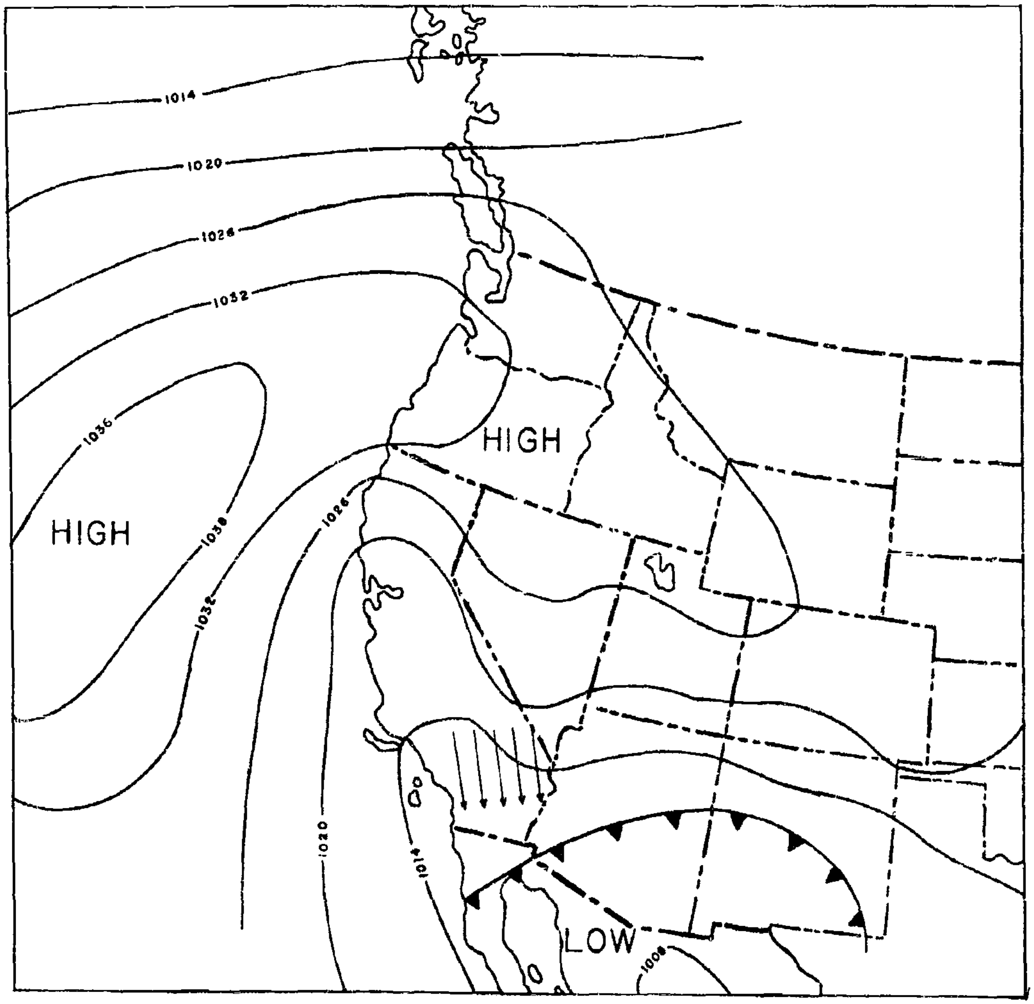

Figure 3. Weather conditions producing sand storm of 27 December 1954.

sand ruined automobile headlights and windshields and severely damaged painted surfaces. All roads in the southwestern portion of the Mojave Desert were closed to traffic for a period of nearly 36 hours. This storm was reported by the California Highway Patrol as being the most severe in their experience.

The windstorm of 27 December 1953 was also caused by the interaction of high pressure off the coast and low pressure in the Great Basin. Winds in excess of 40 miles per hour affected large parts of the desert. Visibility in the areas most intensely affected was between 8 and 12 feet, and sandblasting winds caused heavy damage to automobiles along many of the major highways, especially in the Mojave-Barstow-Baker area.

An intense sand and dust storm in the Mojave Desert occurred on 30 April 1954; this was also caused by the high- and low-pressure relationship just described. A careful perusal of weather charts for the last 5 years indicates that most of the storm-producing winds in the desert are caused by similar weather conditions.

b. Santa Anas

A less common condition producing strong winds in the desert is represented by Figure 4. The resultant wind, known as the "Santa Ana" or "Santana," is a hot wind which blows from the north or northeast across the desert down onto the coastal plain. The pressure relationship producing Santa Ana winds is just the reverse of that described in foregoing paragraphs. A high-pressure cell is centered over Nevada and a low is present off the coast of California. The winds originate in the desert and are typically hot and dry. As they cross the desert they sweep up any available loose dust and carry it across the mountains down into the more populated coastal districts. The dry winds have a desiccating effect on vegetation and a debilitating effect on animal life.

c. Other storm winds

Dust storms are also produced by constrictions in topographic features. As winds of moderate velocity flow through deep gorges and canyons, there is a "crowding" of the air flow lines, and wind velocities increase appreciably. This situation is best exemplified by the storm-producing winds in the San Gorgonio Pass to the north of the Colorado Desert of California. Most winds in this area are the result of marine air moving inland toward areas of lower barometric pressure. Under certain conditions, an inversion layer is formed over the San Gorgonio Pass. The inversion layer has a "capping" effect on air beneath, so that the movement of air is confined to the narrow constriction where its velocity increases rapidly.

A similar situation exists during much of the time when Santa Ana winds blow from the desert through the Cajon Pass between the San

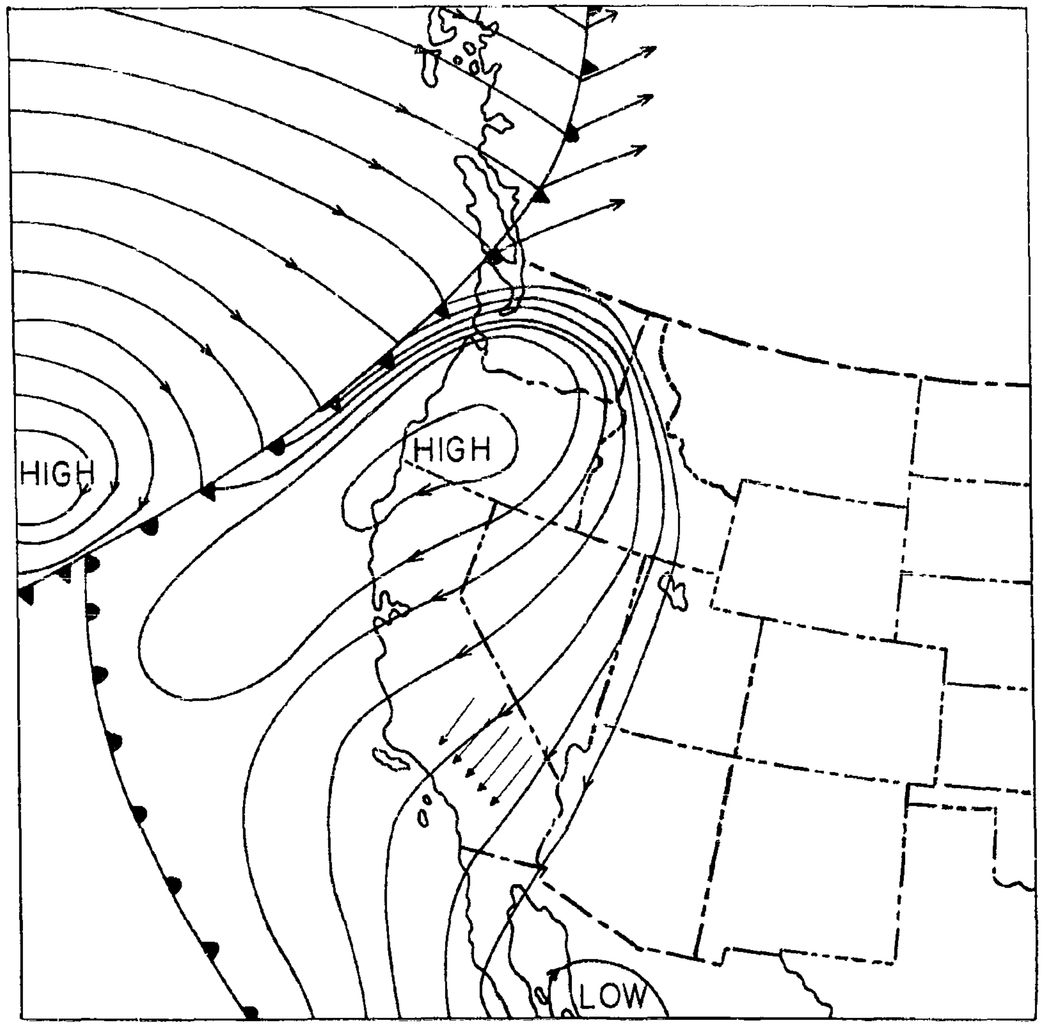

Figure 4. Typical "Santa Ana" wind - 4 November 1958.

Bernardino and San Gabriel Mountains. As the air is forced through this topographic constriction, wind velocity is materially increased, causing storms of dust and some sand in the foothills and plains at the base of the mountains. Wind velocities of 50 miles per hour are not unusual in the San Bernardino region during winter when the Santa Anas usually occur. Visibility during such storms is frequently reduced to such an extent that traffic must be halted, and abrasion damage to vehicles is extensive. Such storms seldom last more than 36 hours.

Another condition producing local winds of sufficient velocity to cause dust storms is associated with many of the basins of interior drainage. In the basins, especially if there is a playa, salt flat, or lava flow in the lowermost portion, a marked diurnal wind cycle is apparent. During the day the air over the flat basin surface is strongly heated, forcing air outward away from the center of the basin. Wind velocities become stronger as temperatures increase during the day. In the evening, winds assume a reverse direction, with flow from the edges toward the center of the basin. Generally, a gradual weakening of the winds takes place through the night, so that there is little or no wind movement by dawn. In some valleys the night winds are hot and persist until sunrise. In Death Valley this type of wind is appropriately called a "furnace wind."

d. Dust devils

Vortical disturbances known as dust devils cause a large number of small dust and sand storms in desert regions. These local disturbances have a very limited extent but are without doubt the type of dust storm most familiar to desert inhabitants. They form as a result of dry thermal convection in arid and semiarid regions. Extreme surface heating of the air leads to low-level instability of the atmosphere. Thus, shallow whirls of upflowing air are initiated, forming chimney-like drafts. The incoming and upflowing air is almost certain to be directed to one side of the center of the rising column and hence a vigorous whirl is established. At the bottom of the corkscrew, loose materials such as fine sand, dust, and organic debris are swept up and carried aloft.

Dust devils move slowly and irregularly about the desert, following the direction of the wind. They occur most commonly during summer and autumn in flat areas where vegetation is sparse or absent. Thus, one would expect to find dust devils on the lower portions of alluvial fans, along dry washes, on playas, and on desert flats. These dust whirls quickly lose their identity on passing from level ground to uneven terrain.

The size and rate of travel of dust devils varies considerably. Some are quite small, being only 1 to 2 feet in diameter and some 6 to 10 feet in height, and travel at a rate of only 1 or 2 feet per second. Most are 10 to 20 feet in diameter and several hundred feet in height and travel

at rates between 5 and 15 miles per hour. An unusually violent whirl near Twentynine was observed travelling at a rate of 33 miles per hour. Buxton (1923, p 29) reported that a dust devil measuring 750 feet in height was observed in Egypt. At Samarra in northern Mesopotamia, several dust devils have been observed that were at least 300 meters (1,000 feet) in height, though only about 5 meters (16 feet) in diameter at the base. Buxton also reports one instance of dust vortices at 5,000 feet, as observed from the air by flying personnel.

Several attempts were made to measure the velocity of the upward-moving air currents in dust devils, but all were unsuccessful. Oliver (1945, p 31) had similar difficulties, but reported that the linear speed of rotation at the outer edge of dust devils in the Middle East ranges from 10 to 40 miles per hour.

Dust devils are common occurrences and usually several are observed during the course of a day. Sometimes as many as six may be counted as they pass along the surface. Because of their limited size, they are generally harmless. They pass rapidly, can be easily avoided, and do no appreciable damage. In the American deserts they are too limited in diameter and height to be of any concern to the aviator. In other deserts of the world, they may be of some consequence. Buxton (1923) states that in 1919 a very large camp northeast of Bagdad was struck by a dust devil of unusual size which carved its way through the camp, leaving a lane in which not a single tent was left standing. Articles of equipment were blown as far as 200 yards and one man was scooped out of his tent with all his equipment and dropped twice, breaking several ribs. No dust devils approaching this size or violence were observed during the present investigation, nor have any accounts of such swirls been reported in the American deserts.

2. <u>Occurrence of sand and dust storms</u>

Observations made during this investigation indicate that sand and dust storms occur almost exclusively in the late winter and spring months. At Victorville, California dust storms are most numerous and intense during the months of February, March, and April; at El Centro, California the dust storm season starts about the first of the year and reaches a climax in March, April, and the first two weeks of May; at Indio, California most sand storms occur during the period from February to April; at Thermal, California wind storms occur mainly during March, April, and May, with a few during November and December; in the vicinity of Mojave, dust storms can be expected from about 1 December to 1 April, with the winds in this region commonly blowing from the southwest; at Parker, Arizona, the acute dusty season is from the middle of February to the middle of April.

Most of the storm-producing winds begin during daylight hours, usually between 1000 and 1400 hours. During many storms the wind blows

steadily throughout the day and early evening hours, abates during the night, and then increases in intensity the next day.

The portions of the desert most susceptible to sand and dust storms are areas where winds are relatively high and where abundant sediment less than 1 mm. in diameter is available for wind transport. Consequently, the principal areas of sand and dust storms are the Mojave-Barstow area, the area along the Mojave wash between Barstow and Baker, the Coachella and Imperial Valleys of the Colorado Desert (where extensive cultivation increases the incidence), the Death Valley-Beatty (Nevada) area, and the area of foothills near San Bernardino.

3. Duration of storms

Information gathered from interviews indicates that most of the sand and dust storms last from 2 to 4 days. This was true at Indio, Parker, El Centro, Thermal, Mojave, Palmdale, and Barstow. In some instances, the total period of blowing sediment represents two separate but consecutive storms rather than a single disturbance. Information obtained from the United States Weather Bureau reveals that individual storms rarely last longer than 48 hours, but on certain occasions one storm may follow on the heels of another, giving the impression of a single, lengthy storm. Udden (1896) believed that sand and dust storms in the Great Basin lasted from 1 to 42 hours and that 32 hours was a good estimate for the duration of any single storm.

Personal observations by members of our investigating group show that most storms last from 12 to 36 hours and rarely continue for more than 4 days. Minor storms of 2 to 6 hours are common and localized storms of the dust devil type may last only a few minutes.

4. Velocity of desert winds

The average velocity of desert winds is surprisingly low, and maximum velocities are far less than might be assumed. Of several hundred measurements of wind velocity made by various members of our investigating group, the highest velocity recorded was 33.7 miles per hour. Included were a series of measurements taken during October 1952 and March 1954 in the vicinity of San Gorgonio Pass and Whitewater Wash, an area known for its persistent winds. The highest velocity recorded during these periods was 27.4 miles per hour and the average velocity was less than 20 miles per hour. All measurements were made when winds were thought to be in the range of 40 to 60 miles per hour. Invariably, however, the measured windspeeds were far below the estimated speeds. It can be concluded from this that a good rule of thumb to apply in estimating wind velocity in the desert is to name a conservative figure and then divide the result by 2.

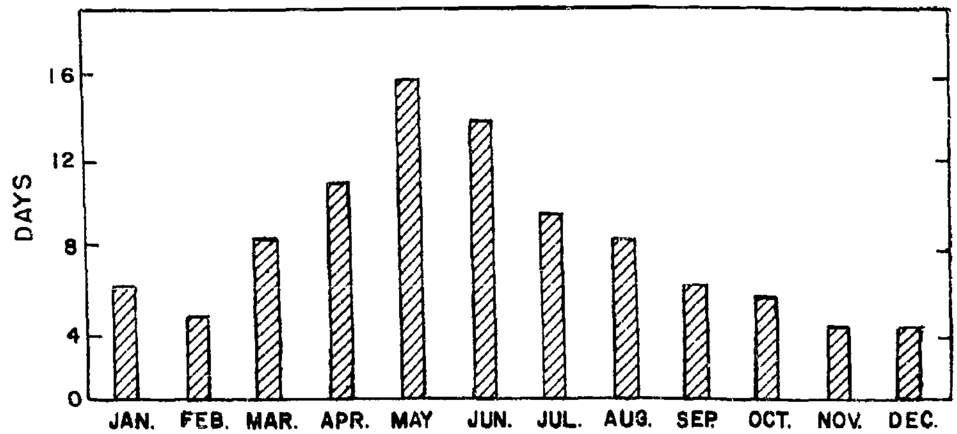

Figure 5. Days per month with winds over 20 mph at Thermal Airport in Coachella Valley, California.

The average number of days during each month of the year from 1946 to 1951 when winds of 20 miles per hour or over blew at the Thermal Airport in the Coachella Valley is shown on Figure 5. The graph indicates that April, May, and June are the months of strongest winds and that windspeeds are lowest during the autumn and winter months. During the 6 years of record on which the graph is based, the daily maximum wind did not exceed 30 miles per hour on 90 percent of the days, and the highest velocity recorded was 60 miles per hour.

At Edwards Air Force Base, Muroc, California, a record of maximum windspeed within various velocity ranges was kept for a 10-year period. The records reveal that for all months during this period the maximum windspeed was between 32 and 46 miles per hour, except in August, when the maximum was between 25 and 31 miles per hour.

Extensive weather records were available for the desert stations at Daggett and Palmdale. Daggett is reputed to be one of the windiest spots in the desert; Palmdale, in the windy Antelope Valley, is exposed to several dust storms each year. Yet, a study of the wind records of these stations again indicates that wind velocity in the desert is much lower than commonly believed.

Hourly readings obtained from 1932 through 1938 at Daggett show that 69 percent of the observations were between 4 and 15 miles per hour, 20 percent between 16 and 31 miles per hour, and 1 percent between 32 and 47 miles per hour; a small fraction of 1 percent were above 47 miles per

hour. Calms prevailed during 10 percent of the time. The maximum wind velocities in miles per hour for each year of the period of record are given below:

1932	1933	1934	1935	1936	1937	1938
49	53	44	52	53	51	50

At Palmdale, wind records for the period from 1934 through 1938 are even more revealing. At this station 62 percent of the observations were between 4 and 15 miles per hour, 22 percent between 16 and 31 miles per hour, 1 percent between 32 and 47 miles per hour, and calms prevailed during 15 percent of the time; on only one occasion during the entire period was there a wind in excess of 47 miles per hour. The annual maximum wind velocities in miles per hour for the period covered are:

1934	1935	1936	1937	1938
41	48	44	44	41

The percentage of days on which the maximum wind velocity fell within each of the given velocity classes during the 7-year period at Daggett and the 5-year period at Palmdale is presented in Figure 6. The graphs emphasize the predominance of winds less than 16 miles per hour and the small percentage of winds greater than 32 miles per hour. They further substantiate the greater frequency of strong winds during the spring months and the more stable conditions existing during the summer and early winter months.

Incomplete wind records for Yuma, Arizona, are available for 19 of the years between 1907 and 1946. They show that the average monthly velocity for those 19 years was about 6 miles per hour, and that the highest windspeed experienced was 40 miles per hour, occurring on 11 May 1907.

It is apparent from these data that the much-talked-of desert winds of 60, 80, and 100 miles per hour simply do not exist. Winds in excess of 50 miles per hour are extremely rare and probably occur only as gusts. Winds in excess of 30 miles per hour can be expected about 1 percent of the time and those over 45 miles per hour only a small fraction of 1 percent of the time.

5. Frequency of storms

The incidence of sand and dust storms is directly related to the occurrence of winds of appreciable velocity. A wind must be over 30 miles per hour to create storms in the desert, in all areas except localities in the lee of sand dunes and sandy areas. The frequency of strong wind storms in most of the desert is certainly not more than 3 or 4 each year and in most localities is only 1 or 2. For example, at Backus Ranch,

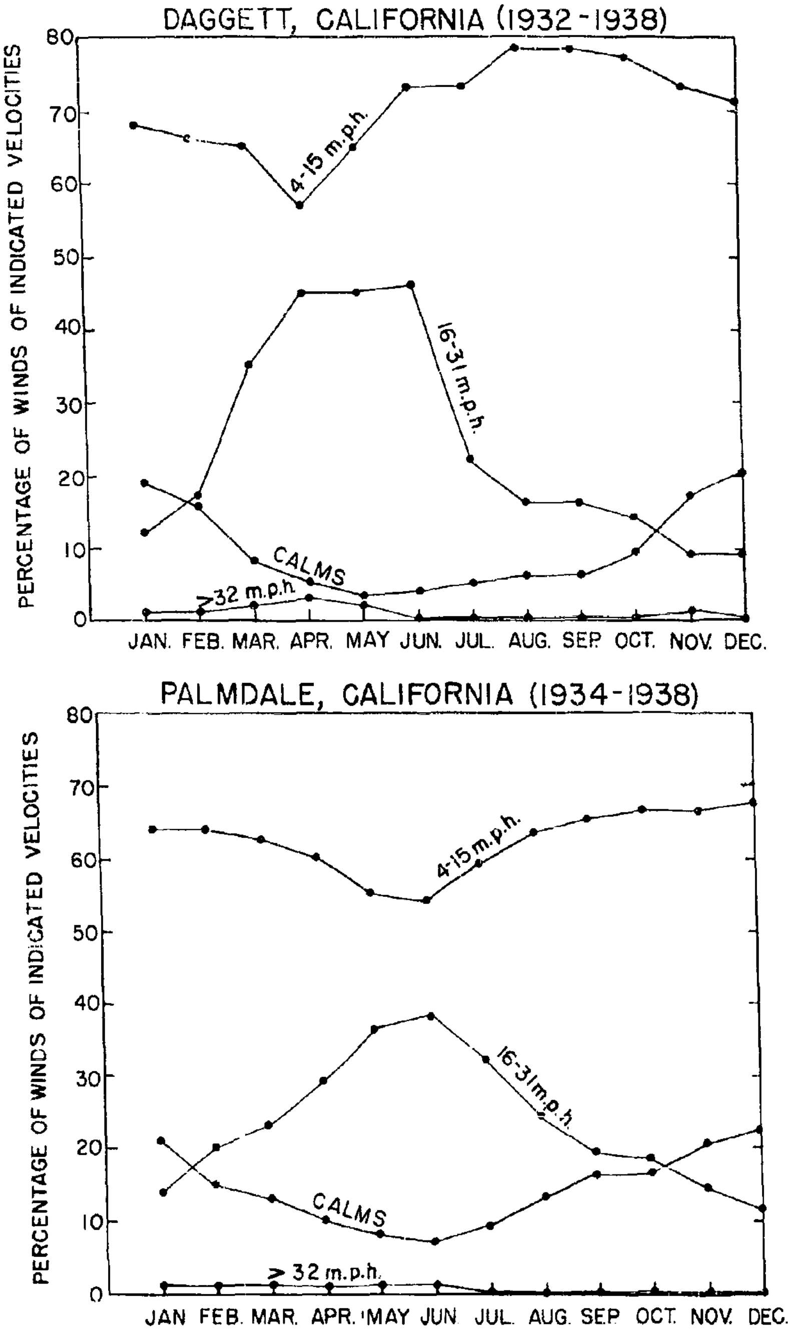

Figure 6. Wind records at Daggett and Palmdale, California.

south of Mojave, the only dust storm mentioned in the records for 1949 occurred on 19 April. At the Naval Air Station at Mojave, during the period 1 March 1943 to 31 December 1943, the airfield was closed only once for a dust storm which occurred between 0600 and 0715 hours on 18 March. At Muroc, California, over a 10-year period, the mean number of days with visibility less than 1 mile caused by blown sand or dust was less than 0.4 of a day per month. Wind records maintained at the Edison substation at Palmdale from 1948 to 1953 show that an average of 6 storms occurred each year. In this case even very small amounts of dust were noted and tabulated as dust storms so that the incidence may be exaggerated at this locality.

It should be remembered that in areas where the surface has been highly disturbed by the activities of man, the frequency of sand and dust storms increases sharply. The most common way in which desert surfaces are disturbed is by the preparation of land for cultivation and the subsequent tillage. In this respect, interviews with several long-time residents of the Imperial and Coachella Valleys indicated that sand and dust storms were 10 to 15 times more numerous in the early days of large-scale farming than they are now. In the highly-cultivated areas of the Colorado Desert, 30 or more dust storms per year occurred during the first few years of tillage. Today, however, with the adoption of many control practices and with permanent crops on large acreages, the incidence is much less, probably not more than 4 or 6 per year.

Another way in which the activities of man disturb desert surfaces is warfare. During World War II when General Patton had his desert training camp in the Desert Center - Parker (Arizona) area, the surface of the land was greatly disturbed by the building of temporary camps and roads and the movement of tanks. The incidence of dust storms was several times as great during this period and for a few years thereafter, due to these disturbing effects.

In the Fort Hood area near Temple, Texas, maneuvering by tanks resulted in huge clouds of dust being raised. The destruction of protective vegetation, the pulverizing of the surface sediment, and the crumbling of surface crust permit the wind, which ordinarily would have little effect, to pick up this material and to cause large dust storms. Similar effects were noted in the vicinity of Yuma Test Station, where tanks and other heavy equipment have destroyed original natural protective surfaces.

A comprehensive survey of dust storms in the western desert of Egypt near Maryat has been made by Oliver (1945) with particular reference to their relationship to the war period of 1939-1945. Such operations as the locating of military establishments, roads, airfields, trenches, fortifications, the removal of vegetation for fuel, detonation of minefields, bombing, and the pulverization of the surface by mechanical traction led to an increase in the number of dust storms. Before the war years the

normal frequency of dust storms was 3 or 4 each year. During 1939, the first year of the war, the number rose to 40; at the height of the war activities in 1941 the number reached 51. As activities decreased during the later years of the war and after, the number of dust storms decreased to 20 in 1942, increased to 26 the following year, and then dropped to only 4 in 1944. Careful inspection of rainfall, humidity, and vegetation records during these years leads to the conclusion that the increase in dust storms and then the return to normal was a direct result of military activities.

6. Visibility

Reports of zero visibility during dust storms are common among natives of the desert, but a close examination of existing records, together with the results of both personal interviews with qualified personnel and also personal observation, indicates that this is not so. At the standard level of observation, visibility is seldom restricted to less than 10 feet during dust storms. In exceptionally severe storms, and for short periods of time only, visibility may drop to 5 feet or less, but such instances are very rare.

During dust storms the bulk of the material transported is within the first 2 or 3 feet of the surface. In this limited zone, visibility may approach zero, but to an individual who is walking or is in a vehicle, visibilities are generally measurable in terms of tens or hundreds of feet. For example, at a point north of Mojave it was estimated that visibility was reduced to ½ mile during the severe storm of 27 December 1953. During the Death Valley dust storm of 4 December 1953 visibility was reduced to 300 feet for a short period. At Edwards Air Force Base (Muroc, California) visibility averaged less than 1 mile during wind storms on only 0.4 days per month over a 10-year period.

7. Other deserts of the world

The sand and dust storms in other deserts of the world differ from those in the California deserts because of the greater abundance of loose material available for transportation and because of the different character of the wind. It was estimated by Clements, et al (1957, p 107), that the dune areas in the southwestern portion of the United States constitute less than 1 percent of the surface area, whereas in the Sahara, Libyan, and Arabian deserts they comprise approximately 25 percent of each desert region. The much larger tracts of sand in the African and Asian deserts greatly enhance the possibility of sandstorms, because critical pick-up velocities are at a minimum in such areas. In addition, in the African and Asian deserts, the winds are much more persistent and often blow steadily in one direction for weeks or even months, while in the California deserts the winds are intermittent and seldom blow steadily for more than 2 or 3 days.

a. Winds of other deserts

In the Egyptian desert a strong wind that blows from the southwest is known as the Khamsin, which means literally the "wind of 50 consecutive days." In the eastern portion of the Iranian Desert a strong wind called the Seistan or "wind of 120 days" blows in from the north. In the Egyptian Sudan the Haboub is a regularly-occurring and persistent wind which causes severe dust storms chiefly between May and September. Other portions of the African deserts suffer from winds that blow so steadily and consistently that they too have been given special names. These include the Shahali, the Sirocco, and the Harmattan, a hot, dry, and dusty wind which blows out of the Sahara. In the Arabian desert a persistent wind called the Shamal blows from May through August. Wind velocity charts prepared at Dhahran, Saudi Arabia (Kerr and Nigra, 1953, p 1544), show for the Shamal a maximum windspeed of 36 miles per hour and an average of 20 miles per hour.

b. Frequency and visibility

The greater abundance of loose material and the persistent and regularly-occurring wind produce a somewhat different sand and dust storm picture from that found in the American deserts. A higher frequency of sandstorms over a wider area produced by winds of lower velocity can be predicted for the African and Asian deserts. Also, the persistence of the winds during certain seasons of the year would tend to increase the incidence and duration of storms.

In the Egyptian and eastern Libyan deserts, Oliver (1945, p 40) noted that the average number of dust storms from 1934 to 1939 was 3 or 4 per year. Visibility during the storms generally was between 50 and 200 meters (about 165 and 660 feet) and only in the most severe storms was it reduced to less than 50 meters (about 165 feet). The most violent storm noted between 1939 and 1946 occurred on 14 March 1941 and affected most of Egypt. At times visibility was restricted to only a few yards and in one locality, Burg, Egypt, the visibility was almost nil between 1100 and 1400 hours. By 1600 visibility had improved to about a quarter of a mile.

An experienced geologist who spent 2 years in the deserts of Morocco and Tunisia reported that strong sand and dust storms occurred only 2 or 3 times each year. Minimum visibility noted during any such storm was 8 to 10 feet. Another observer who had lived 40 years in the Colorado Desert and who also spent 3 years in the African deserts during World War II, reported that the incidence of storms in the African deserts was much greater than in the American deserts. While in Africa he experienced as many as 20 duststorms per year, mostly mild storms. In the Sahara as a whole, many raging storms have been reported, but the violence of the storms and the velocity of the wind are frequently exaggerated, as is often the case in oriental countries (Gautier, 1935, p 15).

8. Effects of windblown sand and dust

a. Abrasive action

The wind, armed with an abundance of dry sand and dust, becomes an important erosive agent in desert regions. Its abrasive effects on natural objects and on equipment and materials taken into the desert are well known in a general way, although there is little quantitative information available on the subject. Strong evidence of the cutting action of the wind is given in many places by rock surfaces exposed to sand-blasting winds. Perhaps the most spectacular example of this type of wind abrasion was observed by the author at Windy Point in the Coachella Valley area where strong winds are forced through a narrow pass between the San Bernardino and San Jacinto Mountains. Here, sand is picked up from a dry wash and carried up and through a saddle in the crest of the spur, forming a climbing dune on the west side and a falling dune on the southeast side. Across the crest in the saddle, the softer metamorphic rocks have been removed by the cutting action of the sand, leaving projecting parallel ridges of granite. Great boulders of granite are grooved along the top and sides, and the side facing the wind has horizontal pits up to 3 inches deep (Fig. 7). Farther down on the windward slope are granite, gneiss, and quartzite boulders as deeply grooved, and in some cases pitted as well.

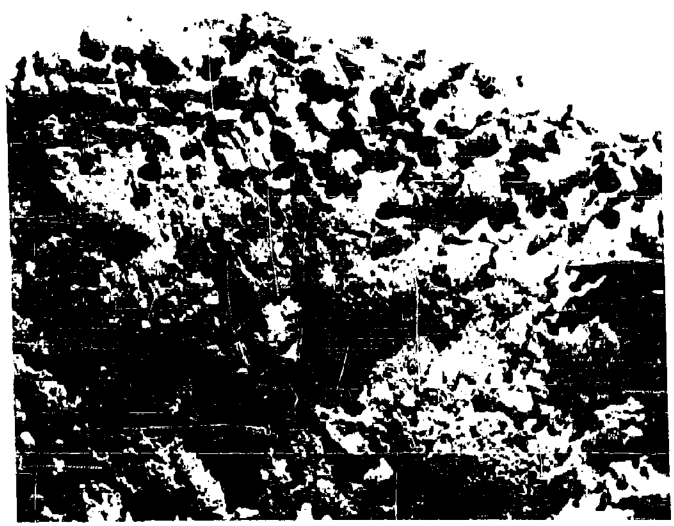

Figure 7. Face of granite boulder on crest at Windy Point deeply pitted by windblown sand.

Objects brought into the desert are highly susceptible to abrasion by windblown sand. The cutting effects of sand are very conspicuous on materials made of wood, such as telephone or telegraph poles, particularly those situated in areas subject to unusually high winds (Fig. 8). Objects made of glass (such as automobile windshields) gradually lose their transparency, first becoming pitted, then frosted, when exposed to sand-blasting winds. The senior author had the windshield of his jeep pitted during a sandstorm in Death Valley on 4 December 1953. During the storm, wind velocities measured by a portable anemometer ranged from 27.8 to 32.1 miles per hour at 6 feet above the ground. The direction of the wind was almost exactly opposite to that in which the jeep was travelling, making the effective velocity about 75 miles per hour. Time of exposure was approximately one hour.

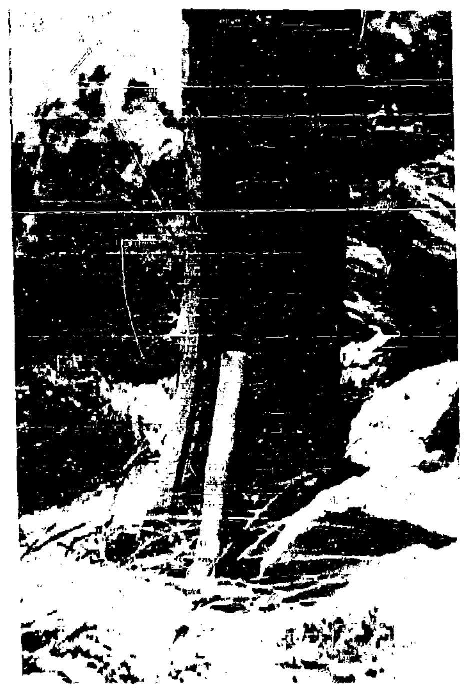

Figure 8. Knots and harder grain stand out on sand-blasted base of telephone pole at Windy Point.

Damage to automobiles is not confined to glass; paint and chrome also suffer. Chromium plating generally is removed from the front bumper, and paint removed from the hood and exposed parts of fenders, front and back. Standing cars are not often damaged by wind-driven sands, but in very intense storms this may happen, and paint is stripped from sides or back as though they had been rubbed by a gigantic piece of coarse sandpaper.

Since most automobiles driven in the deserts of southwestern United States carry insurance against wind damage, a severe and widespread sandstorm can reach disaster proportions for the insurance companies. As a result of the storm of 27 December 1953, for example, a single insurance company had 1,200 claims for wind damage totalling $165,000. The amount of the average claim was $138. and the maximum single claim was $1,500. As a rule, most wind-damage claims are made by travellers passing through the desert. Generally they will drive as long as possible, regardless of the

intensity of the storm, whereas residents of the desert will wait out a sandstorm, except in extreme emergencies.

Maintenance and replacement costs for mechanical equipment used in the desert generally run high. For example, a construction company operating near Parker Dam found that its Caterpillar tractors required new piston rings about every 12 months, compared with an average of every 24 months in less dusty areas. During World War II, the tanks and vehicles used by General Patton's troops on maneuvers near Desert City had a higher than usual rate of engine replacement due to abnormal cylinder wear. Even aircraft are affected. Those operating from unpaved airstrips in desert areas suffer from more rapid cylinder wear and higher rates of oil consumption than normal. As for fixed equipment such as stationary engines, generators, compressors, pumps, machine tools, etc., they too suffer from the abrasive effects of windblown sand and dust. Rings are worn, cylinders scored, commutators scratched, and bearings damaged. Many innovations and preventive measures have been tried to reduce wear on engine parts and mechanical equipment used in the desert. The following are in most common practice: (1) use of air filters on all air intakes; (2) regular and frequent cleaning of air filters, with replacement when necessary; (3) frequent changing of oil in engines; (4) frequent pressure lubrications; (5) use of dustproof housings where practical; and (6) use of snorkel air intakes.

b. Sand encroachment problems

An important property of accumulations of sand is their inherent ability to migrate. Such movement of sandy material results in encroachment on and the partial or complete burial of roads, railroads, airstrips, pipelines, buildings, cultivated areas, and fixed equipment of all types. The control and prevention of sand encroachment is one of the basic tasks which confronts man in any of his activities in desert regions. In the area that was investigated, encroachment problems are relatively minor compared to those in other desert areas of the world, but in a few localities in the California deserts it presents a definite problem. Those areas where encroachment and the abrasion that accompanies it have been problems in the deserts of southwestern United States are shown in Figure 9.

(1) Methods of migration of sand

Dunes and sand may encroach on installations in two manners: (1) by the movement of dunes as entities, and (2) by the movement of sand in sheets and streamers.

Dune movement. Sand dunes, particularly barchans, tend to migrate as entities by removal of sand from the windward slope and deposition of sand on the leeward slope. As the surface grains roll over the crest of the dune they come to rest on the slip or leeward face where they are protected from the bombardment of grains moving in saltation over the windward slope. Sand grains moving over the crest of a dune fall

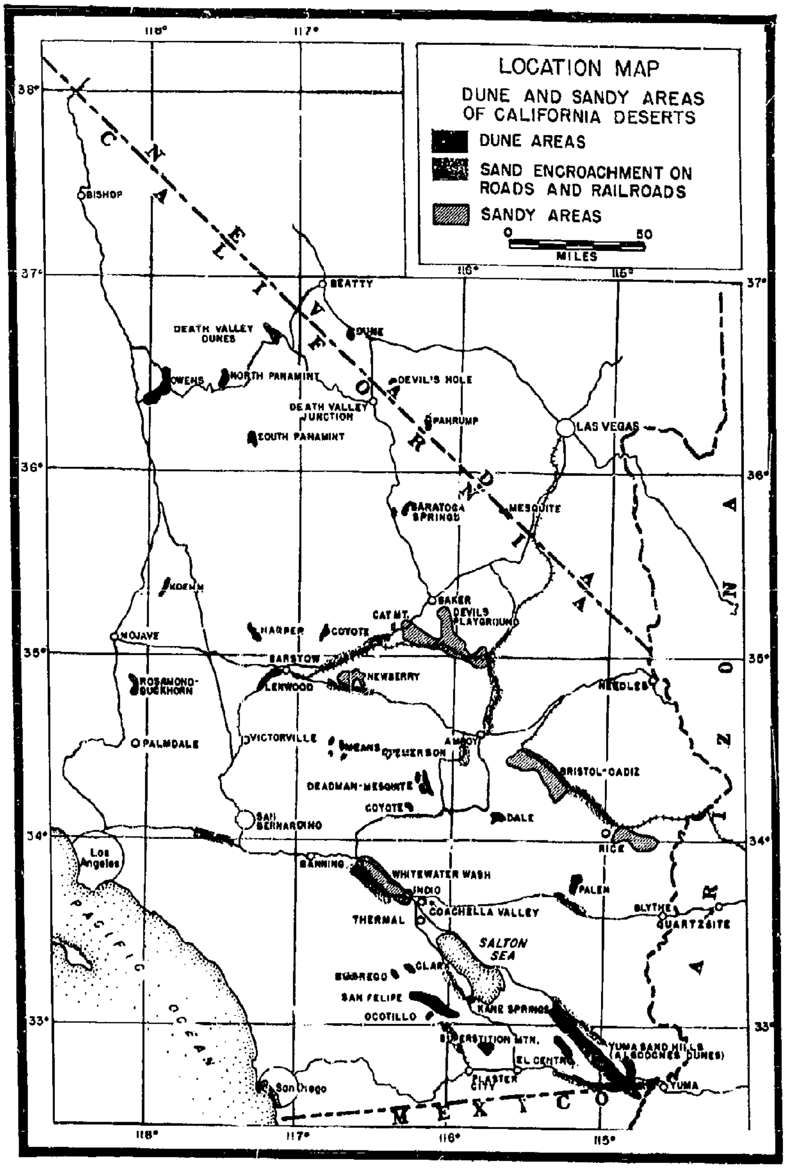

Figure 9. Location map of dune and sandy areas within the California deserts.

gently through the relatively quiet air inside the wind shadow that exists to the lee of the crest. The surface is built up by these grains until the angle of repose reaches 34 degrees, then the face of the dune suddenly shears under the influence of gravity and a small avalanche results (Fig. 10). In this manner a sand dune migrates downwind.

The observation post in the Death Valley dune area made an excellent reference point for observing movement of dunes as entities. Here, the prevailing northwesterly winds funneling down the valley meet Tucki Mountain, which juts into the depression from the west. This partial obstruction causes the winds to eddy and lose velocity, thus bringing about deposition and the formation of dunes (Fig. 11).

Our observation post was set up on 7 March 1953 in the eastern part of the dune area, 240 feet in from the edge of the dunes. It was placed on a clay surface from which the wind had removed the sand, affording a firm base into which the pegs holding the guy wires could be driven. There was no appreciable amount of sand within 20 feet of the post, although there were dunes all around. Three sand traps made of beer cans with tops removed were nailed to the post with their tops at 2, 5, and 7 feet, respectively, above the ground. The post faced northwest into the prevailing winds (Fig. 12).

Figure 10. Shear bands on slip face of falling dune in the Pinto Mountains.

Figure 11. Complex dunes in Death Valley.

Figure 12. Observation post in Death Valley dunes, 7 March 1953.

The post was first visited one month later, on 3 April. At that time the southeast and southwest guy-wire stakes were just covered with sand, indicating encroachment from the south. There was some sand in the lowest sand trap, and a very small amount in the one at 5 feet.

The next visit was made more than 2 months later on 17 June. Sand had continued to drift from the south, forming a small barchan, one end of which buried the southeast stake to a depth of 18 inches. The southwest stake was also covered, and sand had moved to the northeast stake. This small dune was beginning to show a concavity to the northwest.

By 16 July the advancing toe of the barchan had reached the post itself, just covering the base. The southeast guy-wire stake was covered to a depth of 2 feet and the southwest stake to approximately 1 foot. The northeast stake was just covered.

A month later, on 19 August, the sand had buried the base of the post itself, reaching to the bottom of the lowest can. The height at this point was 1 foot, 7 inches above the original surface. All guy-wire stakes were covered to depths from 6 inches to $2\frac{1}{2}$ feet. The lowest sand trap was half full of sand.

On 27 September the barchan showed still further movement to the north. The high part of the dune was southwest of the post, which was in a shallow trough. At the post itself, the sand came to the bottom of the lowest can, but at the crest the dune was $3\frac{1}{2}$ feet above the underlying clay surface. By this time the crescent shape of the dune was well developed, with the horns of the crescent advanced about 20 feet past the post to the northwest (Fig. 13).

When visited a month later, on 24 October, the dune showed a surprising change. It had reversed itself completely and was now facing southeast (Fig. 14). The actual position of the main mass of sand had not changed greatly, except that the crescent tips now reached out to the southeast of the post. The post itself was buried to the top of the lowest can. All 3 cans contained sand, but the highest was now only 5 feet above the sand surface. Between 24 October and 15 November when the next visit was made, little change took place in the position of the dune.

On 4 December there was a strong windstorm in Death Valley with measured velocities up to 32 miles per hour. When the post was visited on 6 December, the whole dune had moved back to the south, uncovering the post and all but the southeast guy-wire stake (Fig. 15). The main mass of sand was not as far removed from the post as it had been in April, but a full cycle of migration had been completed.

That the cycle was beginning again was indicated when the post was next observed on 26 February. The dune had started a second migration to the northwest; 2 of the guy-wire stakes were again covered, and sand had buried the base of the post to a depth of 7 inches.

Figure 13. Encroaching sand has developed barchan shape, concave to the northwest, 27 September 1953.

Figure 14. The barchan encroaching on the observation post in the Death Valley dunes has completely reversed itself, and is now concave to the southeast, 24 October 1958.

Figure 15. Dune that partially buried observation post in the Death Valley dunes has retreated to the southeast, uncovering the post and all but one of the guy-wire stakes, 6 December 1953.

In the 7-month period from March to October, there was mass movement of the dune, from southwest to northeast, of approximately 40 feet. From October to December, barely 2 months, the dune moved perhaps 30 feet in the reverse direction, from northwest to southeast. On the basis of these observations it would appear that the prevailing wind is from the southeast during most of the year, but during the much shorter period in winter when northwesterly winds prevail, velocities are much higher.

Sheet migration. Accumulations of sand in thin sheets also cause encroachment problems. If the ground surface contains obstructions such as pipelines, buildings, or similar installations, or if there is an abrupt change of surface slope, as in the case of a railway roadbed or a road cut, sand grains that are moving by surface creep are held up while those carried by saltation pass on. Materials thus deposited will gradually drift across the road or railroad during succeeding storms and may encroach upon and partially bury fixed equipment.

(2) Encroachment on railroads

Sand encroachment on railroads in the California deserts presents problems in 3 principal areas: the Devil's Playground area,

the Cadiz-Bristol region, and along the small line which the United States Gypsum Company maintains between its factory at Plaster City and the gypsum mine. This latter area was visited and investigated in some detail and is used as a typical example of encroachment on railroads.

This small spur line runs roughly northwest from Plaster City for a distance of about 22 miles. The main area of sand encroachment is between Mile 11 and Mile 16, measured from Plaster City. The area is covered with longitudinal dunes 1 to 3 feet in height. After storms, sand often covers intermittent stretches of track 20 to 50 feet in length and may bury the track to a depth of 2 or 3 feet. In addition to covering the tracks, the sand has the following adverse effects: (1) it mixes with the track ballast and undercuts the edges of the roadbed, necessitating much more maintenance than is usually normal, (2) it fills in the culverts, leading to washouts during rainstorms, (3) it backs up along loading docks, hindering operations, and (4) it is believed to increase the rate of wear on moving parts of railroad equipment.

The movement of sand in the Plaster City area is seasonal. During winter the sand moves out of the west from Carrizo Wash towards the Superstition Mountains. During late spring and early summer the winds blow in the opposite direction and sand movement is from the Superstition Mountains across the tracks toward Carrizo Wash. The sand encroachment problem is worst during the months from February through May.

Several control measures are practiced in this region. The primary controls consist of shovelling sand off the track, clearing out culverts, and constantly adding ballast to the roadbed. Figure 16 shows a stretch of track only 2 months after the track and an adjoining 10-foot strip had been cleared of sand. Control by removal is an endless and expensive process, so in recent years a spreader has been dragged over the dune areas. After the sand has been smoothed in this way it takes about a year for the dunes to reform and reinitiate encroachment. At the time the area was visited the feasibility of installing sand fences was being contemplated.

(3) Encroachment on roads

Sand encroachment on roads not only is a hazard to driving, but also represents a real threat of damage to vehicles by abrasion. The 3 areas where sand encroachment on paved roads is most intense are: (1) on U.S. Highway 80 where it passes through the Yuma Sand Hills, (2) along U.S. Highways 91 and 66 bordering the Mojave River, principally between Barstow and Baker, and Barstow and Needles, and (3) on the highways in the Banning-Indio region. In the encroachment areas small dunes pile up along the edge of the road or may bank along one side of the road, partially covering it. During storms, vehicles using the road are often damaged by thin streamers of sand being blown across the road.

On some of the secondary roads of the desert, sand encroachment is much more intense. Typical of this type of unpaved road are: the road between Rice and Cadiz, those roads in the area of the Devil's Playground, and some of the roads in Death Valley. They are mainly "travel at your own risk" roads, use of which should be attempted as a rule only by jeep or other 4-wheel-drive vehicles. These dirt roads are generally passable to ordinary vehicles after rains, when the sand is well packed and still moist, and may be passable for a month or two after they have been graded. Accumulations of drifting sand not only pose the ever-present problem of becoming stuck on these roads, but in some instances may completely block a road or may cover certain stretches so thoroughly that the road can hardly be distinguished from the surrounding terrain.

(4) Encroachment on cultivated areas

Cultivated areas in desert regions are in constant danger of being covered by migrating sand. Irrigation channels may be filled, young tender plants may be sand-blasted and broken, mature plants may be broken and deformed, fruits may be damaged, and hot, dust-laden winds may cause wilting and scorching. With the advent of intensive cultivation in the Coachella, Imperial, and Palo Verde Valleys of the Colorado Desert of California, many unusual practices have been resorted to in order to protect plants and crops. These practices are discussed in some detail later in the report.

(5) Encroachment on fixed equipment

In the Yuma Sand Hills, telephone poles can be seen that rise only 5 or 10 feet above the level of the sand. These poles have been partially engulfed by dune sands. As encroachment proceeds, a new pole is sometimes attached to the nearly buried original pole (Fig. 17). In other areas buildings and walls are sometimes seen with a thick blanket of sand banked up on the windward side of the structure.

Some of the most troublesome experiences with dune encroachment encountered anywhere were those of the Arabian-American Oil Company during operations in Saudi Arabia in the Abqaiq, Ras Tanura, and Dhahran districts. Their problems included encroachment on roads, drilling rigs, producing oil wells, tank farms, pipe and power lines, and villages and camps.

The laying of pipes presented an especially difficult situation. Generally the pipes are laid at shallow depths since it is desirable (for maintenance and inspection) to prevent the lines from becoming too deeply buried. Scour, on the other hand, frequently results in hundreds of feet of pipe being undermined, and in some cases the pipe hangs from its supports rather than being supported by them. In some cases unsupported lines are laid so that they follow the topography of the dunes. If the dunes migrate from under the pipes in originally high places, they are

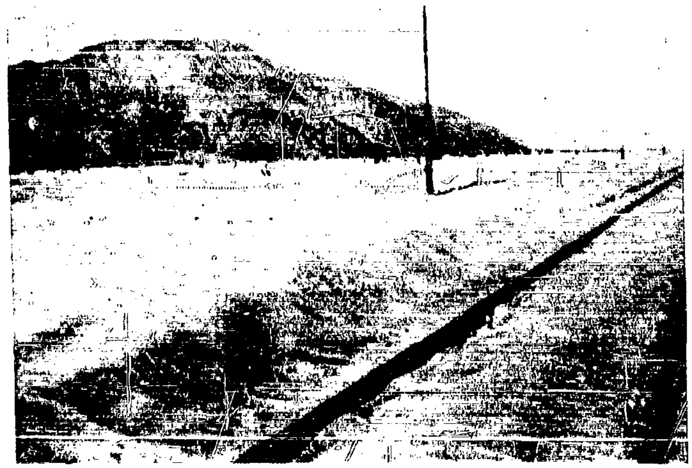

Figure 16. Only two month: ɩer having been cleared, a stretch of tr‥ ʰetween 13 and 14 miles from Plaster City ıɔ again being buried by sand.

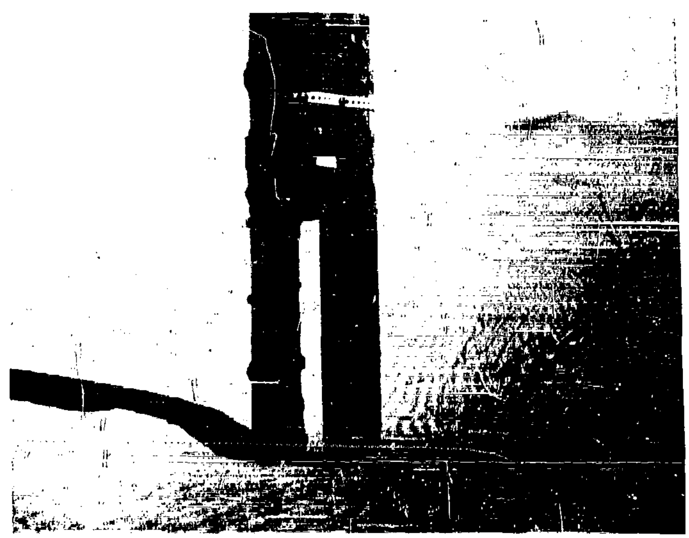

Figure 17. Combatting encroachment of sand on telephone poles by attaching new pole to nearly buried original pole.

left behind looping high in the air. These unsupported loops soon fall over sideways, causing torsion in the lines.

c. Control of encroachment

Many different methods have been tried in controlling movement of wind-blown sand. The most important include direct removal, planting, windbreaks and hedgerows, paving, fencing, panelling, oil stabilization, agricultural methods, and site selection. Each of these is discussed below.

Direct removal. The most direct method of controlling sand movement is to remove the offending material. Hand shovelling, draglines, bulldozers, scrapers, clam-shell bucket cranes, and belt conveyors may be used to remove the sand. Removal is an expensive and almost continuous process, however, and at best is only a temporary solution. For very small accumulations, such as occur along roads and portions of railroads, it might be adequate, but in most cases it is a temporary expedient to be used only while more permanent methods are being considered or installed.

Planting. Plants growing on dunes tend to stabilize the dune and prevent further migration. Planting may be done with seeds or cuttings and by transplanting vegetation that has already sprouted. Herbs and grass as well as shrubs and trees may be used. It is sometimes difficult to get plant growth started in sand, so that it is almost always necessary to irrigate for a year or two. Many plants are used to control migration but some of the most successful are: ice plant, desert croton, European beach grass (Ammophila arenaria), arundo, and oleander. It is suggested that several of the plants native to the dune areas of California, such as Indian rice (Oryzopsis hymenoides) and mesquite (Prosopis juliflora var. glandulosa), might also be useful if planted in large quantities. If a good plant cover can be established, this method might be very effective, but the scarcity of water in arid regions, together with the constant care that is required, usually obviates the attempt.

Windbreaks and hedgerows. Various types of windbreaks and hedgerows are used extensively in cultivated areas to protect crops. Rows of fast-growing shrubs are placed along the edges of cultivated tracts, particularly on the windward side (Fig. 18). Some of the best plants for this purpose are: eucalyptus, tamarisk or athol, desert croton, date palm, arundo, and oleander.

Windbreaks are effective in controlling sand encroachment because they destroy the smooth flow of air across the land surface and because they tend to trap moving sand around their bases. In most cases they are useful in long-range programs only because of the length of time required for the plants to reach maturity.

Figure 18. Row of young tamarisk trees used as a wind-
break for a date palm grove, Coachella Valley.

Paving. One of the most effective methods of control is paving the sandy area. Paving may be done with gravel or pebbles, with concrete or macadam, or as is most common, with crude oil. In Arabia, Kerr and Nigra (1952, p 1156) cite the use of such readily available materials as salt-and-gypsum encrusted sand, gypsiferous marl, water-tamped calcareous clays, and the saline crust of playas.

Paving a sandy area provides a smooth surface for windblown sand to bounce across and be transported to less critical areas. Oiling has been successfully used in California to prevent encroachment on roads, especially along road cuts and in zones where there is a definite change in slope. It has also been applied around the bases of telephone poles in the Yuma dunes (Fig. 19) to prevent encroachment. By piling sand around the bases of the poles and then treating with crude oil, the effects of undercutting and abrasion are generally avoided. Oil treatment of sand was used with great success along the Saudi Arabia Railroad, and has been used extensively in the oil fields of the Middle East. A high-gravity penetrating oil, preferably with a high wax content, applied in sufficient quantity to penetrate to a depth of at least 6 inches gives best results and can withstand fairly constant travel.

Constant wetting of a dune, though not a type of paving, will temporarily control dune migration. In addition to the cohesive effects obtained by wetting, the water used generally contains alkali and other salts and in time will build up a surface crust which aids in the control

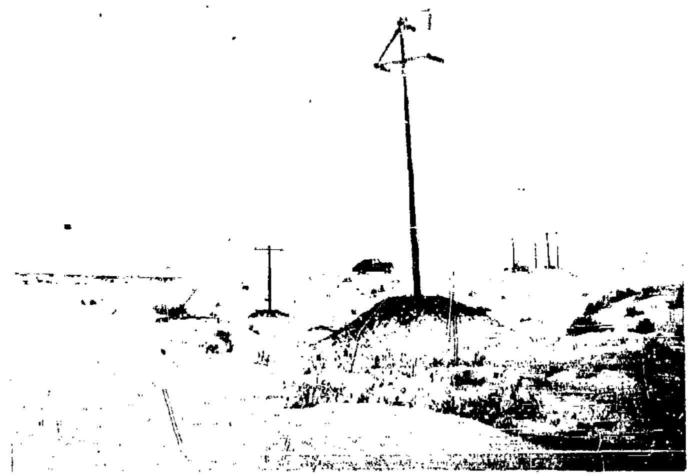

Figure 19. Pole protected from encroachment by oiling of sand around base, Yuma dunes.

of sand movement. Wetting of a dune gives immediate relief, but is effective only as long as the sand is kept moist or until an unbroken salt crust has developed. The scarcity of water and the expense of keeping the sand moist excludes this method from serious consideration in most instances.

Fencing. Another type of control used a great deal is the installation of sand fences (Fig. 20). These fences are similar to snow fences and are generally constructed from laths, palm fronds, or board slats, solidly wired together and secured to supports. They are placed in the path of the encroaching sand, causing deposition to take place against the fence.

Panelling. Panelling involves the installation of wooden walls or panels to divert the wind and thus protect a valuable and permanent installation. They have also been used to protect buildings by installing them on the windward side where windborne sediment accumulates against the panel rather than against the building. Panels have also been used directly on a dune to produce turbulence and thus destroy the streamlined form of the dune. In this manner the rate of dune movement is greatly reduced, although it is never entirely stopped. Consequently, it is frequently necessary to move or enlarge the panels, a relatively expensive operation. Hence, this method has generally proved to be impractical, and is useful only to protect very limited zones for a short period of time.

Figure 20. Use of sand fences to control encroachment of wind-blown sand.

Oil stabilization. Oil stabilization is an important method of dune control. This method is differentiated from paving with oil in the results desired. The purpose of paving is to aid the migration of material so as to prevent its gathering at a specific site. The smooth surface provided, whether by oil or other substances, enables encroaching sand to move by saltation past a location that must be kept clear. Oil stabilization, on the other hand, either immobilizes a dune or contributes to the dune's self-destruction.

To stabilize a dune the entire windward face is treated with a high-gravity penetrating oil. This treatment fixes the dune and prevents further migration. Sand added during later storms will be trapped behind the stabilized dune and will continue to be trapped until the dune eventually reaches a new streamlined profile. When such a stable condition has been reached, the dune will again begin to migrate and further treatment of oil is required.

Dune destruction by oiling is accomplished by treating either the center or the horns of a dune. This allows the untreated portions of the dune to break loose from the stabilized section and re-form down-wind in a series of much smaller dunes. These in turn can be treated with oil and destroyed.

Agricultural methods. In cultivated areas there is danger not only of sand encroachment but also of severe dust storms caused by the breaking up of the surface crust. Inasmuch as many military activities disturb the ground surface in the same way that cultivation does, some of the agricultural controls that are applied should be of interest from a military standpoint.

By irrigating soil before plowing, it is often possible to form slick clods which lie on the surface and are capable of resisting wind for a considerable period. This practice, known as wet-clod cultivation, has been used to a considerable degree in recent years in the desert areas of California. Deep-furrow tillage is another method of controlling sand and dust in cultivated areas. Deep furrows are plowed into the fields and the crops are planted in the deepest portions of the furrows. The furrows are made at right angles to the prevailing winds and the rough surface that is formed is more resistant to wind erosion than the usual smooth surface. Trashy surfaces on a field are also effective. Corn stalks, cotton stalks, straw and other similar crop residues are left on the surface of fields instead of being turned under. Other agricultural methods include planting cereal cover crops between rows of other plants, and planting grass and cereal strips to provide protection for annual crops which will be planted later.

Site selection. Intelligent site selection, though not an actual control practice, is the best means of avoiding extreme sand encroachment and the effects of windblown material. Results obtained at various observation posts during the present study show that the intensity of sand abrasion and sand movement is directly related to the type of desert surface. Alluvial fans, desert flats, volcanic areas, playas, and surfaces covered with desert pavement are much less subject to wind erosion than areas bordering large dry washes, active dune areas, and sandy notches on mountain flanks.

d. Sanitation and housekeeping problems

In areas of periodic duststorms, infiltration of dust into interior spaces creates problems of sanitation and housekeeping.

Sanitation. A problem of sanitation that must be contended with is the contamination of drinking water and food. In the desert, where water is so vital, it is particularly necessary to insure that all water supplies are adequately and carefully protected from unexpected windblown material. Reports of inexperienced desert travellers having their water muddied by sudden wind flurries are all too common. It is not unusual to hear of silt and dust working their way into canvas water bags, with the result that the water becomes unpalatable. Similarly, it is essential to keep foods covered and well wrapped at all times to prevent contamination by windblown material.

Housekeeping. The infiltration of grit and dust makes good housekeeping difficult. In certain portions of the Imperial and Coachella Valleys of California, it was found that in new houses equipped with storm doors and specially-sealed windows, very fine-grained dust persisted in working its way through the most minute openings and into the house. This ability of fine-grained material to enter buildings poses many problems for the military. The storage of bearings, gears, delicate aircraft instruments, electric equipment, etc., requires the exclusion of foreign material of all sizes.

A telephone company near Thermal, California, found that in some of its relay rooms dust would sift into spaces between the relay contacts and prevent or hinder their operation. The same company experienced excessive abrasion of some switches. The damage was so severe that the company was forced to carefully seal the rooms and to install new air-conditioning and filtration equipment to combat the dust.

Controls. The infiltration of dust can be controlled to a substantial degree by the installation of dust-preventive equipment and the practice of regular and frequent maintenance. Perhaps the most common practice is to install adequate air-conditioning systems and to make sure that the filters are regularly cleaned and replaced. In critical buildings an outer storm door should be installed and weather stripping used around all possible entrances. Even with these precautions it is likely that some dust will work its way into the building.

e. Electrostatic effects

It has long been known that the impact of windblown particles produces large electrostatic voltages. During the dust-bowl condition of the mid-thirties in the Great Plains area of the United States, Choun (1936) and Sidwell (1938) reported that ignition systems of some automobiles would not operate during dust storms unless the frame was grounded by a wire or chain. Near Lubbock, Texas, one utility company reported that insulators, transformers, and lightning arrestors often broke down during a sandstorm even though no lightning discharge had occurred. In Saudi Arabia electrostatic charges of as much as 150,000 volts have made telephone and telegraph communications of a railroad inoperable during sandstorms.

Heavy electrostatic charges are sometimes dangerous or demoralizing to personnel. One telephone company official reported that during a sandstorm in the Imperial Valley of California electrostatic voltages high enough to knock a man down were built up on a bare wire that was being laid. While not usually dangerous, electrostatic charges are generally annoying to personnel, and make them reluctant to handle electrical equipment.

Other phenomena perhaps attributable to electrostatic charges are the shearing off of green wheat at the ground level and the stripping of needles from conifers such as fir and spruce. Ball (1927) has made some interesting comments on the effects of electrostatic charges on sand pick-up and deposition. He suggests that sand carried into the upper atmosphere assumes a charge by conduction equal to 100 volts per meter of height. He further believes that the gathering of sand into elongated dunes is the result of electrostatic attraction, the attractive force becoming strong only when the travelling sand grains are within a few millimeters of the dune surface. He also suggests that movement of charged grains may be started in part by their dancing upward because of electrostatic attraction.

The effects of electrostatic charges produced by the friction of dust and sand particles during storms can be avoided by adequately grounding equipment with a wire or piece of metal chain and by thoroughly shielding the electrical systems of such equipment. Men working with wires and with electrical equipment should wear insulated gloves and use insulated tools. Precautions that normally are taken when dealing with live wires of relatively low voltage should also be practiced.

SECTION II. CRITICAL WIND VELOCITIES

1. Previous studies

The most comprehensive work in determining the relationship between wind velocity and the movement of sediment of different particle size has been done by Bagnold (1937, 1941). His research was performed principally in the laboratory above smooth surfaces and with incoherent sand in a very limited range of sizes. The results of his work are summarized in Figure 21. This graph is adapted from his work and that of Garrels (1951) who made certain modifications.

A few words of explanation are necessary to understand the graph. The "fluid threshold" is defined as the wind velocity at which sand movement is initiated as a result of wind pressure alone, while the "impact threshold" is the windspeed required to: (1) bounce rolling grains into the air, and (2) upon their descent downwind, to knock other grains into the air by impact, the impinging grains generally rebounding into the air themselves. It should be noted that the ordinate of the graph is not a measurement of wind velocity. It is a measure of wind gradient Vt, whose threshold value varies directly with the square root of grain diameter. Higher wind gradients therefore are required to transport grains of increasing size. Similarly, the windspeed necessary to initiate particle movement increases with increasing grain size, and the graph can therefore be roughly applied to the problem of pick-up velocities.

With this in mind, the graph shows that the velocity at which a particle of a given diameter will be moved in saltation (by impact) is less than that at which it will be moved in suspension, with the exception of particles less than 0.1 mm. in diameter. This relationship is indicated by the dashed portion of the curve, which shows a sharp increase in velocity for the very small grain sizes. Surfaces formed by the accumulation of small-grained materials are smooth, and the drag of the wind is distributed evenly over them. On smooth surfaces the individual grains are too small to form wind eddies of their own, as is the case with the larger grains of a rough surface. Bagnold (1937), using a layer of loose Portland cement powder, found it impossible to set the particles into motion with a wind velocity of 50 miles per hour.

The graph can also be used to trace the reaction of sand grains to varying wind gradients. For example, grains of 0.4 mm will be carried off and erosion will take place at wind gradients of 31 or more cm per second. At gradients between 23 and 31 cm per second, grains of this diameter will move only by saltation, and at gradients below 23 cm per second they will be deposited, if already in motion. The upper limit of sediment movement by the wind, as indicated by the graph, is slightly greater than 1.6 mm. However, the graph does not show wind gradients higher than 50 cm per second.

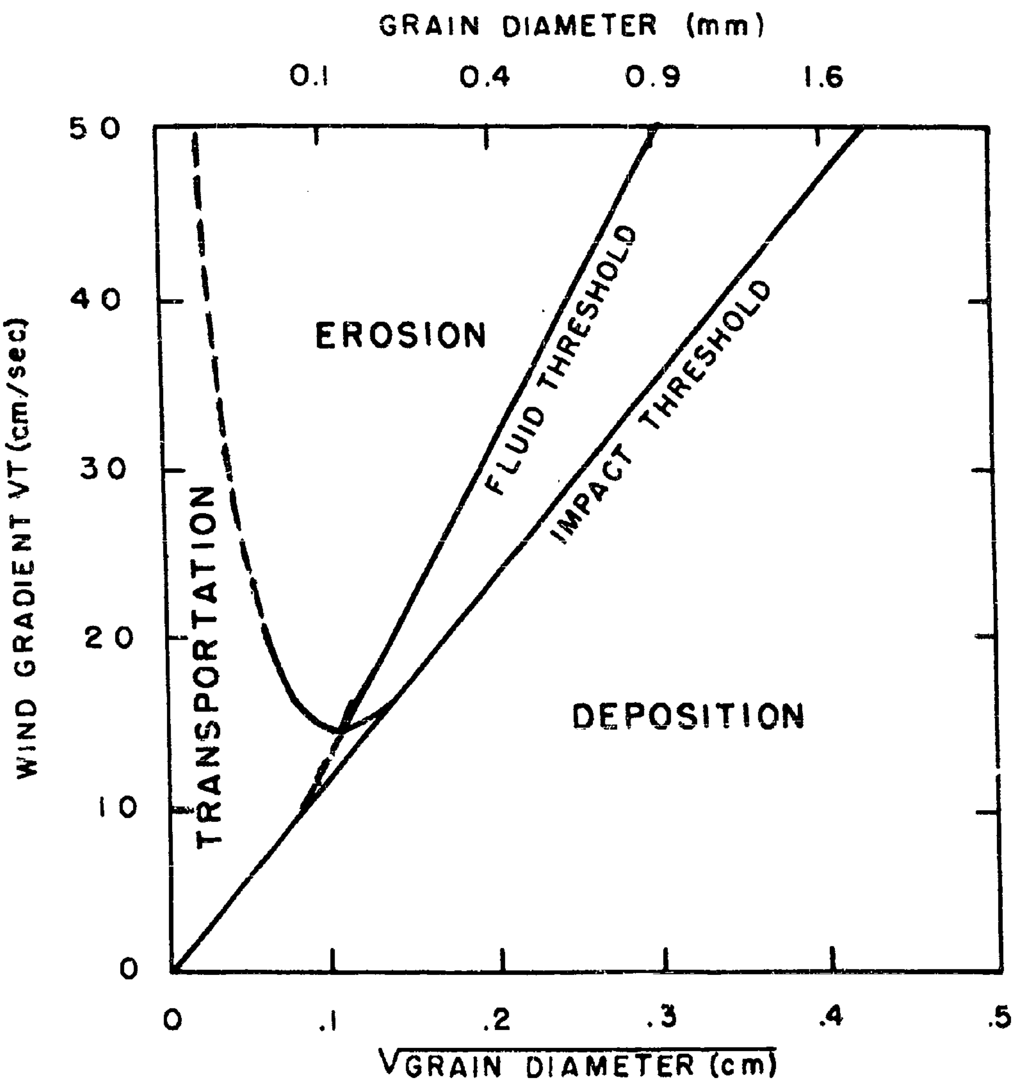

Figure 21. Relationship between grain size, wind gradient; fluid and impact thresholds and the transportation, erosion, and deposition by the wind.

2. Critical velocities by grain size

Originally it was intended to develop a graph showing critical pick-up velocities in miles per hour for sediment grains with diameters from 0.1 mm to 2 mm. As the investigation proceeded it was soon realized that such a graph would be practically meaningless. If a dune sand were sieved and the velocities at which the various size groups were set in motion then determined, any set of values derived from this information would apply only for a very limited set of conditions, most of which do not exist in nature.

Some of the variables that affect the pick-up velocity of sand grains are: surface irregularities, the gustiness of the wind, the degree of rounding of the sand grains, the degree of sorting existing in the surface materials, the amount of moisture present, the dimensions of the surface over which the wind blows, the degree of coherency of the surface material, the type of movement that takes place (whether creep, saltation, or suspension), and to some extent the height above the surface at which the wind velocity is recorded. Thus a single curve showing the relationship between pick-up velocities and grain size has little true value and even less application to field conditions.

However, from work performed in the field and from work of previous investigators, some useful generalizations can be made. These are: (1) grains greater than 2 mm in diameter will not be set in motion by winds less than 50 miles per hour, and it is exceptional when grains as large as 4 mm in diameter are moved, (2) as the grain diameter decreases below 0.08 mm, the velocity required to move these fine grains increases sharply and when the grains are in the fine silt and clay range (2 microns and less) they are not moved by winds in excess of 50 miles per hour, (3) grains whose diameter is 0.20 mm will be moved at wind velocities as low as 11 miles per hour, (4) sand grains between 0.08 mm and 1 mm will generally be transported under the influence of winds whose velocity is between 11 and 30 miles per hour, and (5) sand grains of 1 mm to 2 mm in diameter will be transported at velocities of 35 to 45 miles per hour under ideal conditions.

3. Critical velocities on surface types

a. General

In order to obtain sufficiently accurate velocity control for determining threshold pick-up velocities over various types of natural desert surfaces, a blower was constructed and transported to the field. The blower was turned by a pulley arrangement and a variable speed motor which made it possible to obtain a range of wind velocities between 9 and 35 miles per hour. The duct leading from the blower consisted of 3 detachable sections so that the entire machine could be transported into the

desert and then carried to the selected site. Wind velocities produced were measured by a portable anemometer and a portable manometer. The manometer was designed and constructed to measure simultaneous velocities at several different levels. It is similar to the type commonly used in wind tunnels and consists of pitot-static tubes connected by rubber tubing to glass tubes of variable inclinations.

In using the blower, the motor was first set to produce a windspeed of approximately 10 miles per hour; thereafter speeds were increased in 3-mile-per-hour increments to the maximum speed possible (about 35 mph). As soon as movement above the surface was noted, samples of the transported materials were collected by holding sample bags 10 inches from the end of the duct. These samples were then brought to the laboratory and analyzed for maximum, minimum, and median diameters, and histograms showing size distribution were drawn. The portable blower was used on 6 different types of desert surfaces, namely: sand dunes, desert flat, dry wash, desert pavement, alluvial fan, and playa. Each of these is discussed below. The locations of the velocity test sites are shown in Figure 22.

b. Sand dunes

The sand dune area selected for velocity testing is located about 2 miles northeast of the town of Twentynine Palms. The dunes consist of transverse ridges averaging 3 to 5 feet in height. The crests of many of the dunes are fixed by vegetation. The material of which these dunes are composed is quartz sand, mostly between 1/4 and 1/8 mm in diameter (fine sand). The blower was placed on the leeward slope of a large transverse dune which rose about 4 feet above the general terrain, and was run at speeds to produce velocities of 10.6, 13.0, 16.4, 20.6, 25.6, 30.0, and 35.1 miles per hour. At a velocity of 10.6 miles per hour a few grains on the surface between 1/8 and 1/16 mm in diameter began to move by surface creep. At 13.0 miles per hour grains began to move by saltation and some very fine material was carried in suspension. The median diameter of the grains moving at this speed was 0.175 mm. As the velocity was increased, more and more material was moved and the grain size of the material transported increased proportionately. At 25.6 miles per hour the median diameter of the material being transported was 0.19 mm; at 30 and 35 miles per hour the median diameter had levelled off at 0.20 mm. The critical pick-up velocity on a sand dune where the grains consist of fine sand is about 13 miles per hour, and fine and very fine sand will move by creep at a velocity as low as 10 miles per hour. Figure 23 shows the wind machine in operation at the Twentynine Palms dunes at a velocity of 30 miles per hour. The large quantity of material being transported is clearly apparent and it is interesting to observe that the greater amount of material is being moved within the first inch or two above the dune surface.

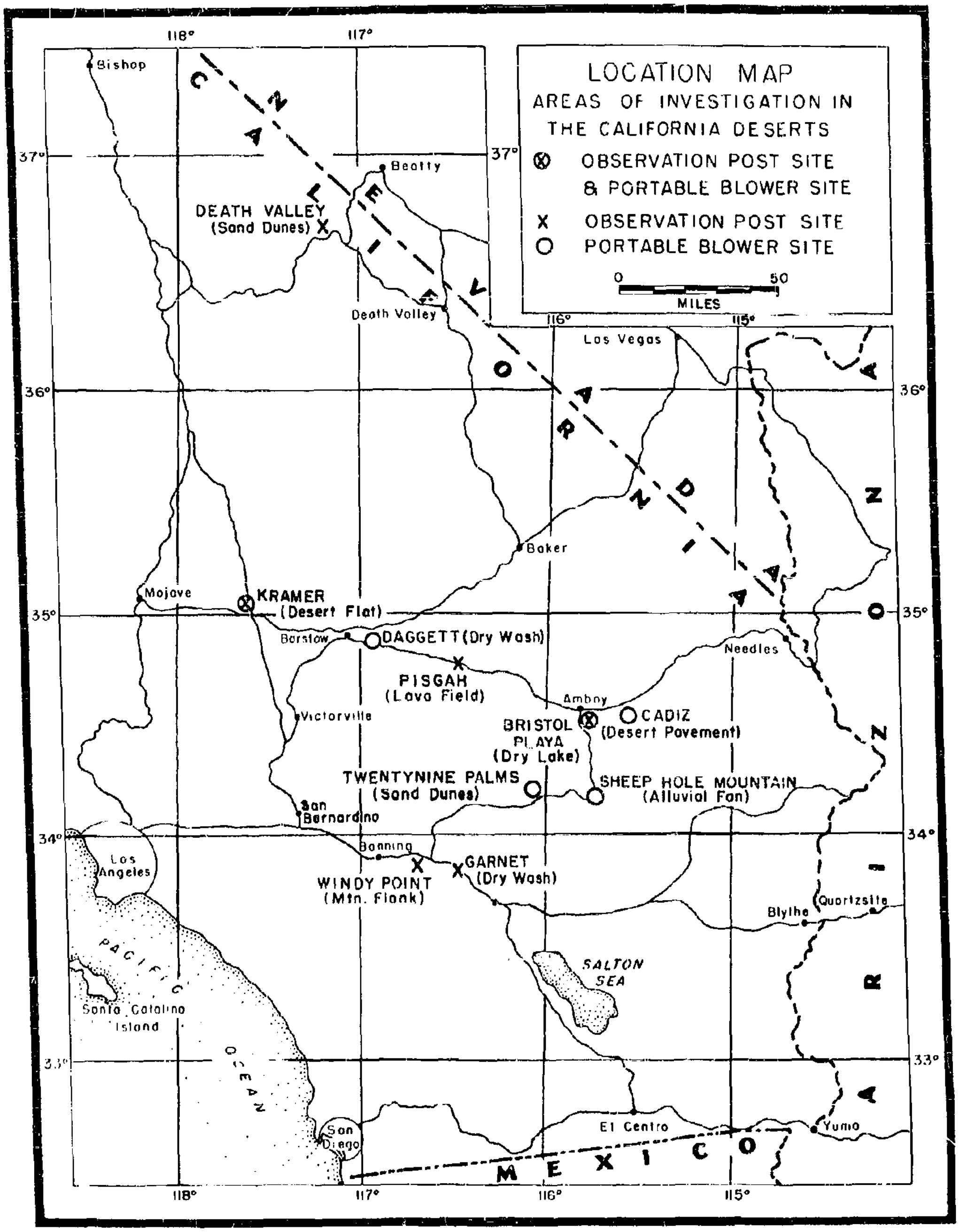

Figure 22. Location map showing areas of investigation.

Figure 23. Blower in operation on dunes in the vicinity of Twentynine Palms. The velocity at the time photograph was made was 30 mph.

c. Desert flat

Critical pick-up velocities over a desert flat surface were tested in an area adjoining the Kramer observation post. At a velocity of 14.5 miles per hour there was no movement of dust or sand. When the blower produced a wind of 18.1 miles per hour there was minor movement of dust-size material in the form of a series of very small eddies. No creep or saltation took place at this velocity. At 20.0 miles per hour a very limited number of grains of sand size began to move, largely by creep and a few by saltation. The first important movement took place at a velocity of 25.4 miles per hour. Six percent of the material moved was between 1 and 2 mm (very coarse sand), and 63 percent of the material was less than 1 mm in diameter and greater than 1/16 mm in diameter, that is, within the fine-to-coarse sand range. Only 4 percent of the material moved was silt size, between 1/8 and 1/256 mm in diameter. The median diameter of the material transported at this velocity was 0.30 mm.

When velocity was increased to the maximum possible (35.4 miles per hour), there was a pronounced increase in the quantity of sediment being transported. The amount of very coarse sand that was being moved increased to 21.6 per cent and the amount of silt increased to 7.6 percent. At this higher velocity about 10 percent of the material being carried

off was in the form of clay and silt curls or chips which were torn loose from the crusted surface of the valley flats. It might be expected that with the increased distance of transportation these curls would break down into their component parts and give rise to even more suspended particles. The bulk of the material transported at the lowest speed was transported by surface creep. At 25.4 miles per hour the majority of the material was being carried in saltation; at 35.4 miles per hour saltation effects were still dominant, but the amount of suspended material had increased considerably.

d. Dry wash

The Mojave River is one of the major drainage channels in the Mojave Desert. This river is dry most of the year and along its course there is an abundant source of sand. The region along the Mojave River to the east of Barstow is one of the areas of most pronounced sand abrasion and sand encroachment in the deserts of southwestern United States. Consequently, a site within the Mojave wash at a point about ½ mile north-northeast of the town of Daggett was selected for testing pick-up velocities within a dry wash. A view of the blower operation at the Daggett site is shown in Figure 24. The dry wash at this locality is about 200 yards in width. The sand in the river bottom has a median diameter of 0.61 mm, i.e., in the size range of coarse sand. Of the total, 6.5 percent was very coarse sand, 47.4 percent coarse sand, and 43.4 percent medium sand.

Figure 24. Blower in operation in the Mojave River dry wash near Daggett.

First movement of surface material was recorded at a velocity of 18.4 miles per hour when minor surface creep of the finer grains occurred, along with surface creep of small clay curbs which were mixed with the surface layer of sand. The median diameter of the material moved at this velocity was 0.295 mm, and represented the finer portion of the source material. At 21.9 miles per hour pronounced movement by saltation took place; the grains being transported had a median diameter of 0.48 mm. No material in the coarse or very coarse sand groups was moved at this velocity.

When a velocity of 24.7 miles per hour was attained, about 1 percent of the material moved was between 1 and 2 mm (very coarse sand), and the remainder was largely in the medium and fine sand divisions, the median grain diameter having increased to 0.44 mm. At 29.5 miles per hour the median diameter had increased to 0.47 mm; at this speed 12 percent of the material was coarse sand, although the bulk remained in the 1/8 to 1/4 mm size group. The critical pick-up velocity for movement along a dry wash where there is abundant material in the medium and coarse-size group is about 22 miles per hour, although creep may be initiated at lower speeds.

e. Desert pavement

On the alluvial fans bordering the flanks of the Marble Mountains and about a mile north of Cadiz Station is an area of desert pavement in the process of development. This area was used for the test because it was believed that in an area of maturely-developed pavement no results could be obtained, inasmuch as the finer material would have long before been removed. Pavement that is maturely developed has an armor of material on the order of 30 to 80 mm in diameter which, of course, could not be transported by the wind. At the Marble Mountain site sufficient fine-grained material remained to give an indication of the velocities necessary to transport it.

The surface material at the Marble Mountain pavement was made up of granules 2 to 4 mm in diameter, very coarse sand, 1 to 2 mm in diameter, and between these larger particles, considerable quantities of finer sand and some silt. No movement of any sort was observed until a velocity of 19.4 miles per hour had been reached. At this speed no material greater than 0.5 mm in diameter was moved and 77.8 percent of the material being transported was between 0.5 and 0.125 mm in diameter. When the speed was increased, the larger particles began to move, and at 20.3 miles per hour 1.5 percent of the material was between 1 and $\frac{1}{2}$ mm in diameter; by 33 miles per hour 1 percent of the material was very coarse sand (1 to 2 mm). At this maximum speed 67 percent of the material was between 1/4 and 1/8 mm. The larger granule-size material was not affected. This process showed the manner in which well-developed pavements are formed. The finer material is removed and the coarse is left behind in the form of lag gravel; this eventually forms a smooth mosaic which protects the

underlying material from further wind erosion. The critical pick-up velocity on a surface of partially-formed desert pavement proved to be approximately 19 miles per hour.

f. Alluvial fan

The alluvial fan used for the critical pick-up velocity test is located on the southern flank of the Sheep Hole Mountains about 3 miles north of Dale Dry Lake. The surface of the fan is composed of material mostly in the coarse sand and granule-size groups. Occasional cobbles and boulders are also found on the surface. Mixed with the coarse sand are minor amounts of finer material, almost all of which is in the medium and fine sand groups. A view of the Sheep Hole fan with the blower in place is shown in Figure 25.

It is important to note that the surface of the fan had a pronounced crust. In and beneath the crust, which is not easily broken, there is abundant material which could be transported by the wind, but, since much of it is more or less cemented to the coarser material in the crust, the possibilities of transportation by the wind are greatly reduced. As the blower speed was gradually increased from an initial velocity of 20 miles per hour to 30 miles per hour, no movement took place. Movement of surface material was first noted at a velocity of 33.4 miles per hour when particles whose median diameter was 0.137 mm were transported. Only a very small amount of sediment was recovered at this velocity. At a maximum blower speed of 35.7 miles per hour, the amount of material recovered increased slightly and the median diameter increased to a value of 0.14 mm. The largest grains recovered had a diameter of 1.3 mm while the smallest were 0.008 mm, silt size.

The critical pick-up velocity for alluvial fans with a thin surface crust is approximately 33 miles per hour. On alluvial fans which do not possess such a crust, or where recent sedimentation has contributed an abundant source of loose fine material to the surface, the critical velocity would be considerably less. It is estimated that the critical velocity under these conditions would be on the order of 20 miles per hour.

g. Playa

The Bristol playa was chosen for testing critical pick-up velocities on a dry lake surface. The surface at Bristol consists of a definite crust made up largely of salts, clay, and silt. Adhering to the crust and mixed into the material beneath the crust were sand-size particles which made up about 6 percent of the sediment. The median diameter of the material in the sand-size particles was 0.24 mm. The crusted surface of the playa with the blower in operation is shown in Figure 26.

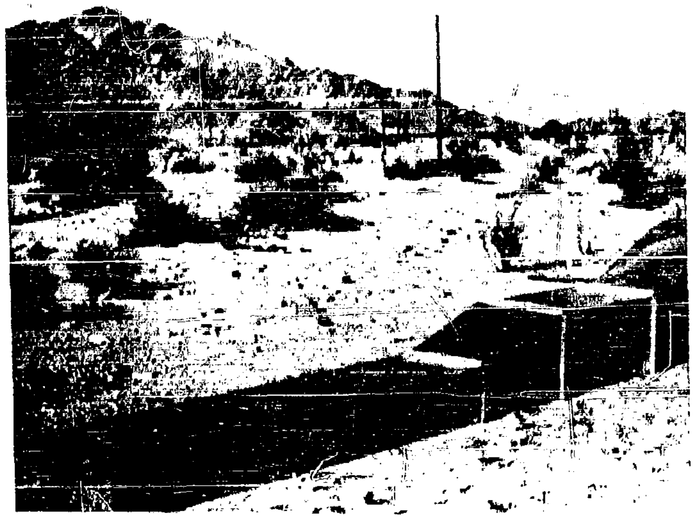

Figure 25. Blower in place on alluvial fan on the southern flank of the Sheep Hole Mountains.

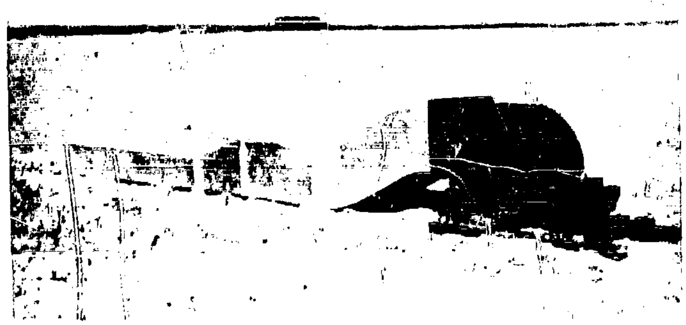

Figure 26. Portable blower in operation on Bristol playa.

First movement of the playa surface occurred at 21.3 miles per hour and the material transported consisted entirely of fine aggregates of crystalline salt, which is found in a thin crust on the surface. Initial movement of non-saline sediment took place at a velocity of 22 miles per hour, but the volume of material being transported was negligible. Grain size analysis showed that the median diameter of this material was 0.12 mm. At a velocity of 33.2 miles per hour the amount of sediment moved was still small but the median diameter had increased to 0.215 mm. The material transported consisted of aggregates of silt and salt rather than individual particles, with only minor amounts of sand. These aggregates were not broken down to particle size in the laboratory for analysis since, as aggregates, they represented the actual size of material being moved at the test velocity. When the surface crust was broken and the underlying material exposed to the effects of the artificially-produced wind, large amounts of sediment, principally in the silt size, were set into motion.

The undisturbed surface of a playa is very stable. The finer material available for transportation is protected by a highly cemented surface crust. Winds in excess of 33 miles per hour would be required to raise a dust or sandstorm on a dry lake of this type.

4. Results and conclusions

a. General

The results of the observations made with the portable blower are summarized in Figure 27 by a series of 6 histograms showing the increase in grain size of sediments moved with increasing velocity over different surface types. The histograms on the left show the size distribution of sediment moved at lower velocities and those on the right at higher velocities. They all indicate that with increased wind velocity there is an increase in the median diameter of the material translocated; moreover, there is an increase also with amounts of the larger-sized materials being transported. The variation was least pronounced at the Twentynine Palms dune locality where there was no material larger than 1/2 mm in diameter available for wind movement. Even so, the amount of sediment in the largest-size group, 1/4 to 1/2 mm, increased with increasing velocity. At the same time, there was a corresponding decrease, percentagewise, in the 2 smaller-size groups. Further results showing the increase in grain size with velocity increase, and more important, the critical pick-up velocities, are presented in Figure 28.

From the data shown on the plates, and from the foregoing discussion in this section, it is evident that critical pick-up velocities on natural surfaces are primarily a function of the degree of coherency of the surface material and of the grain size.

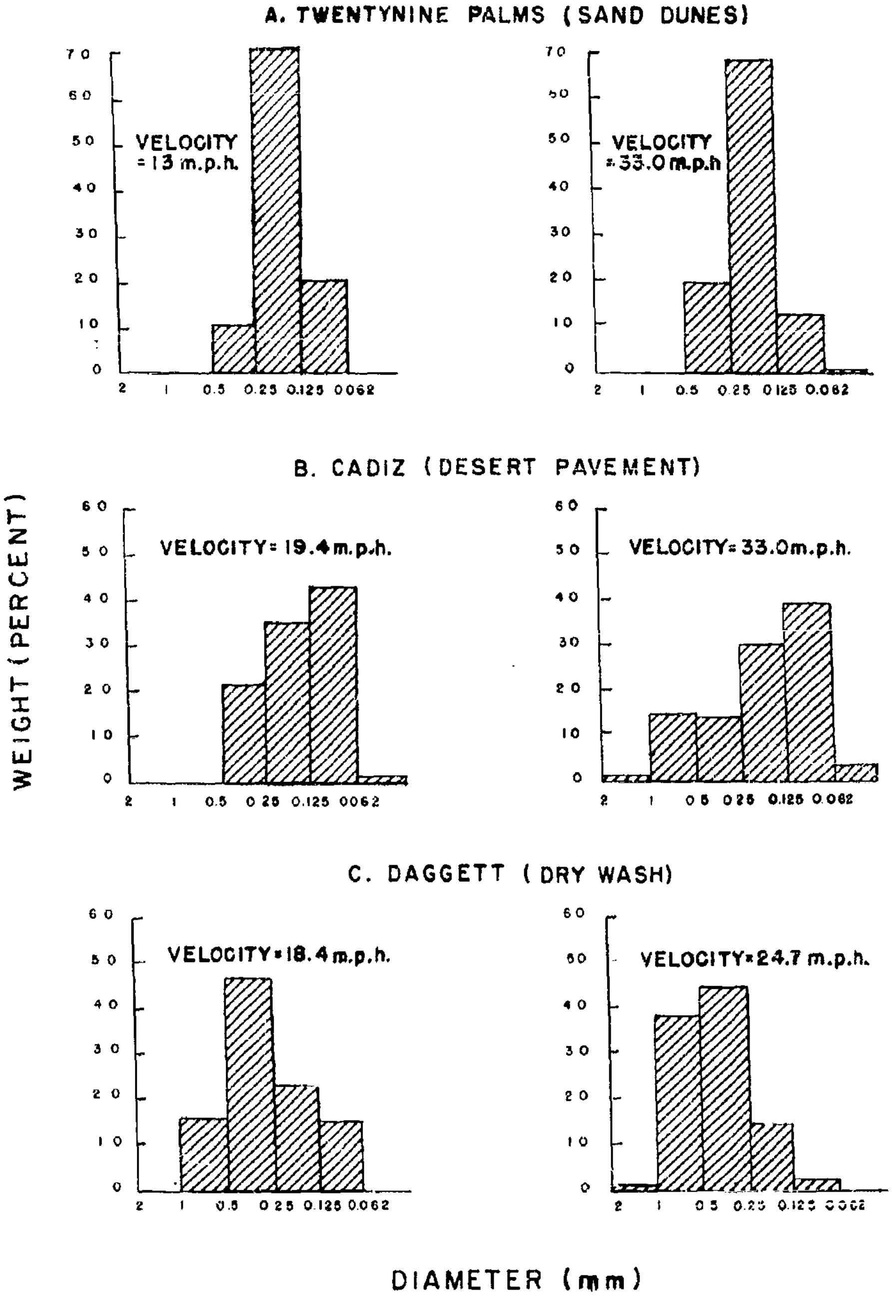

Figure 27. Histograms showing variation in sediment distribution with differing artificially produced wind velocities.

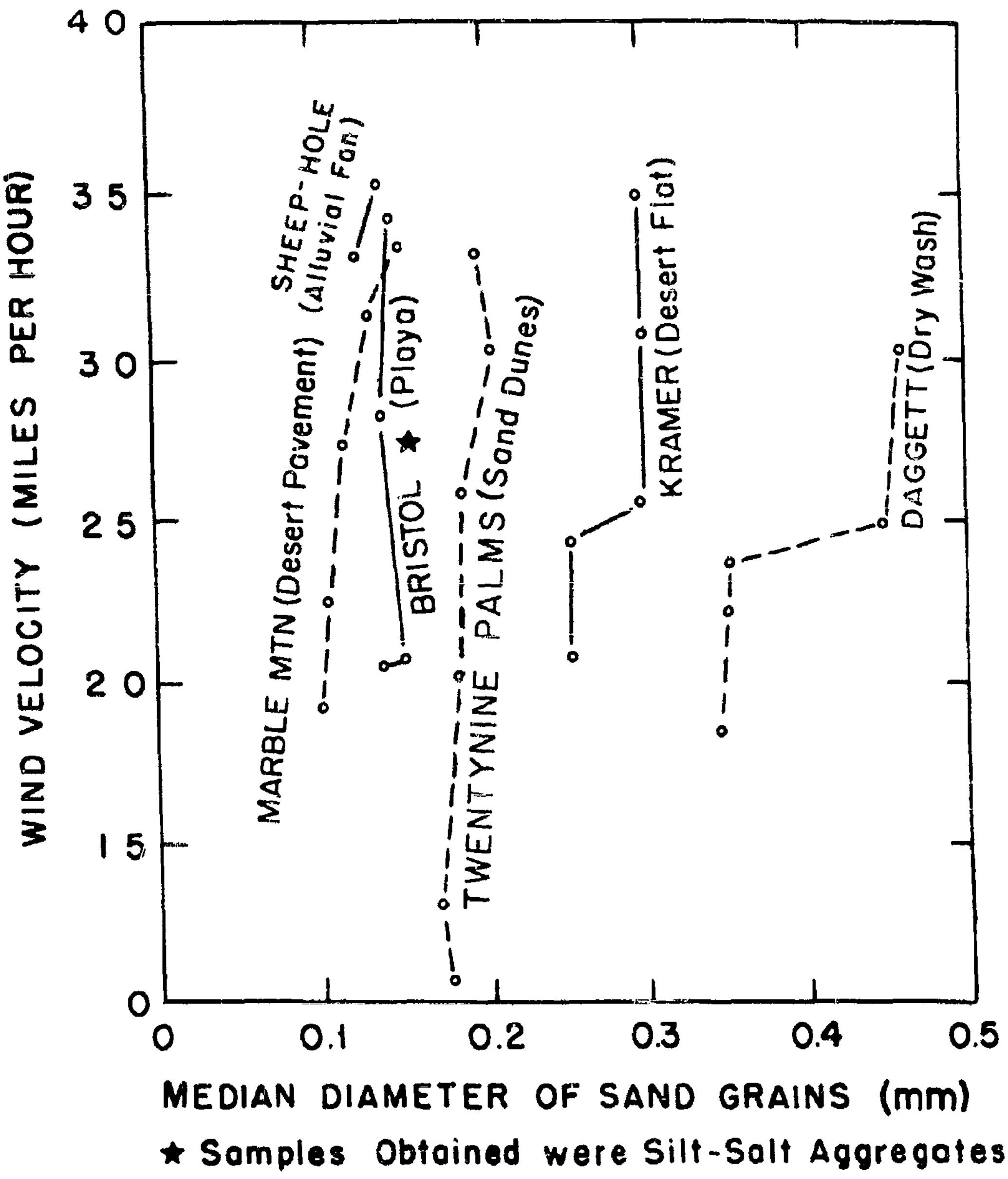

Figure 28. Variation of median diameter of material transported with varying artificially induced wind velocity.

b. Degree of coherency

In some areas, a highly coherent surface crust or armor protects sediments that ordinarily would be susceptible to wind transport. This was especially true at the playa lake site, the alluvial fan, the desert flat, and the areas of desert pavement. In the last-named, protection is afforded by a mosaic of pebbles, and little if any material is picked up by winds blowing over the surface. At playas, very little movement was noted even at velocities higher than 30 miles per hour.

In contrast, critical pick-up velocities are relatively low in areas where the surface sediments are incoherent. In the dune area the initial movement took place at about 10 miles per hour and along the dry wash at about 19 miles per hour. Above other surfaces such low velocities had little or no effect. Yet when the surface crust was broken and the underlying material agitated, the critical pick-up velocity was materially reduced.

c. Grain size

The grain size of the available material is the second consideration of importance. In areas of desert pavement where granule and pebble-size materials are on the surface, no transportation takes place at all, whereas in sand dune areas where the sediment is made up of fine or very fine sand, the pick-up velocity is extremely low. In areas of incoherent material the pick-up velocity was greatest in that area where the median diameter was largest, as shown by the tests performed at Twentynine Palms and Daggett.

d. Critical pick-up velocities on specific surfaces

The critical pick-up velocity on specific surface types varies over fairly wide limits in relation to the grain size of the surface material and with the degree of coherency of this material. Thus, it would be improper to state that on all alluvial fans, for example, the critical pick-up velocity is a definite number of miles per hour. Nevertheless, fairly definite relationships between wind and its capacity to transport sediment over specified surface types are suggested by the results of the velocity tests.

At wind velocities of 10 to 15 miles per hour, movement will be initiated in dune areas consisting of fine to medium sand, and at 20 miles per hour, pick-up will take place in other sandy areas. Fine material on the surface of desert flats will be transported in most cases at velocities of 20 to 25 miles per hour. In regions of crusted alluvial fans and on many playas, movement can be expected to start at between 30 and 35 miles per hour. On well-developed desert pavement little if any movement will occur at velocities less than 40 miles per hour, but if the desert pavement is not well developed, movement can be expected at velocities as low as 20 miles per hour. If the ground material on any of these surface

types has been recently disturbed, as by wheeled vehicles or flood alluviations, the critical pick-up velocity will decrease and a higher incidence of wind-blown material at lower velocities can be anticipated.

SECTION III. VERTICAL DISTRIBUTION OF WINDBORNE SAND AND DUST

1. General

One of the most significant parts of an investigation of windborne sediment concerns the height above the surface at which the material is transported by the wind. Is the load carried by the wind distributed evenly throughout the first 10 feet above the surface? Is it carried largely near the surface? Or is the load near the surface almost negligible? This portion of the study is concerned with answering these questions and will deal with transportation of sand and dust within the first 6 to 8 feet above the ground.

2. Previous investigations

Studies of the distribution of airborne material relatively close to the surface have produced much interesting information. The first 1 or 2 feet above the surface is the most critical zone. Bagnold (1941) has shown that over any given surface, regardless of the velocity of the wind, there exists a thin zone of still air. It has been found that the height to which the wind velocity is zero is approximately equal to 1/30 of the diameter of the sand grains or pebbles of which the surface consists. For example, if the surface material consists of pebbles 15 mm in diameter, the air from the surface of the ground on which they rest to a height of 0.5 mm is still, and any wind movement that takes place is above this level.

Above the layer of "still air" the velocity of a given wind increases rapidly with increased height above the surface. Bagnold (1941, p 48) produced 2 experimental curves by plotting wind velocity against height above the surface. These show a sharp increase in velocity within the first few feet of the surface, followed by a flattening of the curve to a nearly constant velocity. Similarly, Kerr and Nigra (1952, p 1543) presented some of the work of Meyers who conducted studies to show relative variation of wind velocity with height from the ground. In the curve he obtained, a sharp break in a rapidly-uptrending curve for a wind velocity of 13.5 miles per hour was noted at a 10-inch height above the surface. At a height of 6 feet the curve had flattened out considerably. These writers estimated that 95 percent of the total sand movement is within 10 inches of the ground surface. This is based mostly on information from funnel tests made during sandstorms which showed that the weight of sand caught in the funnel started to decrease when the funnel was held as high as 12 inches above the ground and was negligible at a height of 30 inches.

Stallings (1951) made extensive investigations of the mechanics of soil erosion and found that most of the soil movement in saltation is below the height of 2 to 3 feet. In his experiments, over 90 percent of

the soil transported was below the height of 12 inches, and more than 50 percent remained below the 2-inch level. Stallings also showed that the rate of transport is largest near the surface. The rate of flow between the surface and the 38-inch height amounted to about 490 pounds of sediment per hour per 1 foot width of surface for an 18-mile-per-hour wind, and 990 pounds for a 25-mile-per-hour wind.

Results of previous investigations can be summarized as follows: (1) above 0.5 millimeters where a still air zone always exists, wind velocity tends to increase rapidly, (2) the wind velocity and hence the carrying capacity increases rapidly within the first few feet of the surface, but increases only very slowly above this height; (3) material that is carried by the wind is for the most part set in motion within the first 12 to 18 inches of the ground surface and most of this is carried within the first 10 inches or less.

3. Results of field experiments

a. Data from observation posts

Information regarding the vertical distribution of windborne material was obtained principally from a series of observation posts erected at strategic positions on representative types of desert surfaces. The posts consisted of two-by-fours set into the ground to a depth of 1/2 to 2 feet and extending 7 to 8 feet into the air. One of the wide sides was faced in the direction of the prevailing winds. To collect wind-carried sand, 2 and in some cases 3 containers were attached to the posts at intervals of 2 or 3 feet from the ground surface (Fig. 29). These containers were open at one end and faced in the direction of the prevailing wind. Some of the containers were set with the long axis horizontal and others with the long axis vertical. To collect finer-grained detrital material, 4 x 6 cm glass slides were coated with petroleum jelly and placed at different heights on the upper half of the post. The test posts were under observation from March 1953 to May 1954, a period of 14 months. Each of the posts was visited monthly, and at each visit the material retained in the containers was removed and brought to the laboratory for analysis. Late in May 1954, all equipment was removed from the posts and taken to the laboratory for comparison and analysis. Sites at which post observations were taken are: Kramer (desert flat), Pisgah (lava field), Bristol (dry lake), Windy Point (mountain flank), Garnet (dry wash), and Death Valley (sand dunes). The locations of the observation posts are shown in Figure 22.

Materials obtained from the observation posts were analyzed in the following ways: (1) from the grain size distribution of the petroleum-jelly-coated slides, (2) from grain size analysis of material trapped in the sediment containers, and (3) from the relative amounts of material trapped in the containers. (It should be remembered that these results

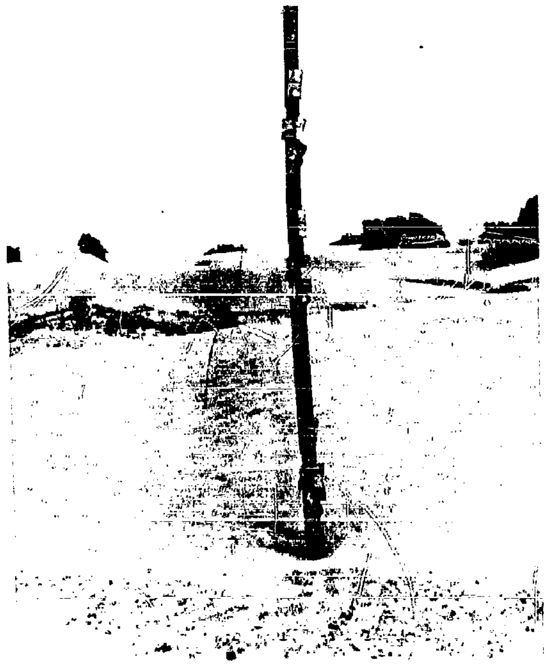

Figure 29. Observation post with sediment traps attached in Death Valley dunes area.

are indicative of average conditions, since the sediment collecting took place over a period of months, and represent the effects of one or more windstorms of varying intensity.)

Material on glass slides. Results of the analysis of the material trapped on the petroleum-covered slides give an indication of grain-size variation with increasing height. Maximum and minimum diameters were determined by means of a micrometer scale attachment to a petrographic microscope. The degree of rounding of the grains and also the mineralogical content were determined under the microscope. The slides from which the sediment was obtained were located at 2 levels on the posts, the upper slides at a height of 72 inches above the surface and the lower at 48 inches.

A comparison of the maximum and minimum diameters for both the upper and lower slides at 5 localities is shown in Figure 30. The maximum diameter of sediment trapped on the lower slides was 0.49 mm, obtained at the Bristol post, and the average maximum size at the 5 posts was 0.38 mm. These stand in strong contrast to the corresponding sizes measured for the upper slides which were 0.29 mm for the maximum diameter obtained at Windy Point, and 0.20 mm as the average maximum for the 5 upper slides. There

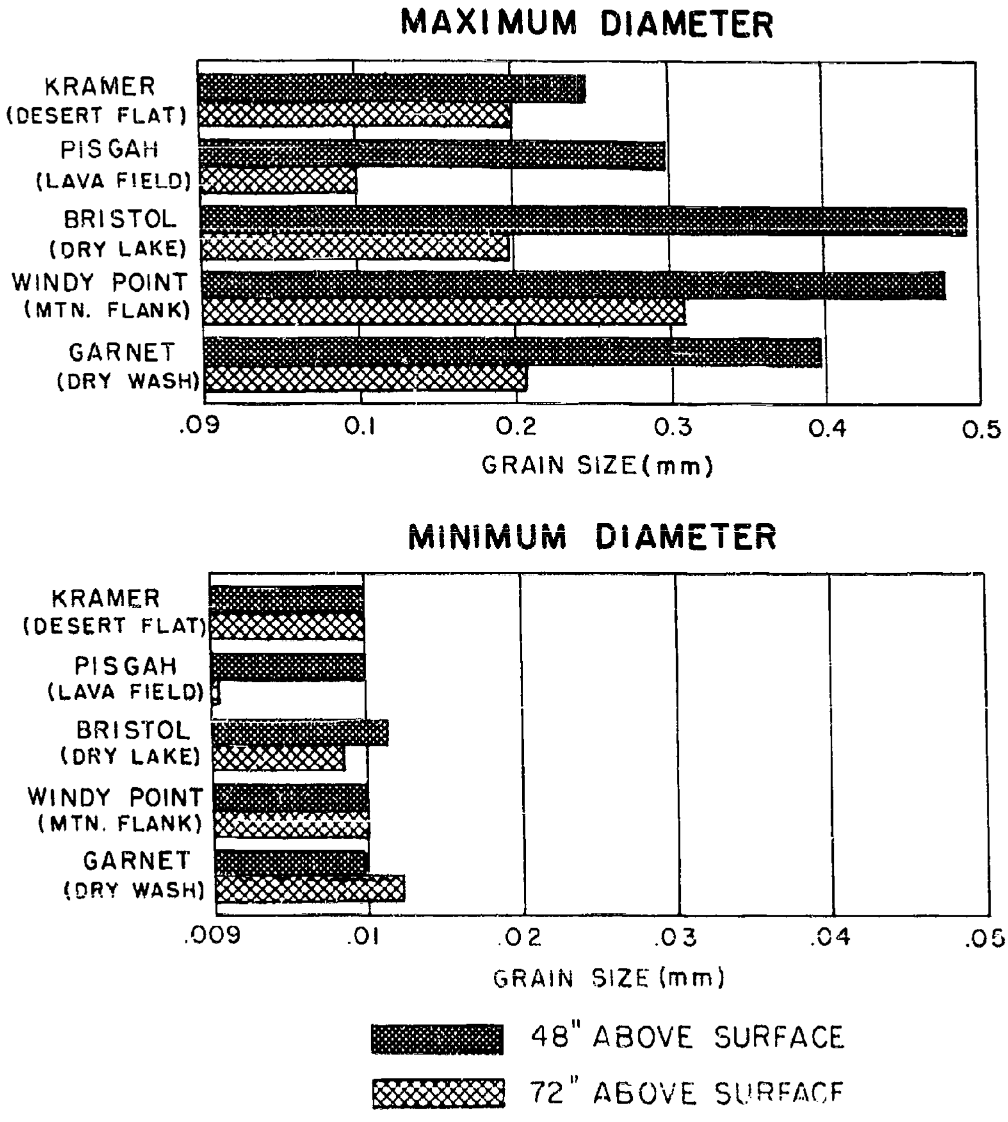

Figure 30. Maximum and minimum diameters of sediment trapped on the petroleum jelly slides.

was an apparent variation of about 0.20 mm between the maximum diameters found on the lower and upper slides in each instance.

The minimum diameter of grains on the upper and lower slides showed little variation, being 0.009 and 0.012 mm, respectively. This materiel (dust size) was trapped indiscriminately at both the lower and the upper levels on all posts. The deviations were so minute that it was necessary to plot them on a different scale than the one used for maximum diameters, so that the differences could be shown.

It can be seen that for very fine-grained material (less than 0.01 mm in diameter) there is no appreciable variation in the size of material carried within the lower 6 feet of the surface. With coarser material, particularly at diameters above 0.20 mm, there is a distinct relationship between grain size and height above the surface. The upper slides consistently had finer material, and at each station the material of maximum size (upper) was approximately 0.20 mm finer than that on the lower slides.

Sediment traps on wind posts:

Grain size. The analyses of the material in the sediment traps on the observation posts showed similar results. The material that accumulated in the lowermost containers, which were placed 3 to 5 inches above the surface, was, with one exception, coarser than the material in the upper traps, which were situated 26 inches and in some cases 84 inches above the ground surface. This information is presented in Figure 31 as a comparison with the median diameter of the source material in the area of the sediment trap. This was believed necessary since there is an obvious relationship between grain size of the material transported at different levels and the grain size of the material available for wind movement. It would be possible for the sediment trapped in the upper container in a region of coarse material to be much coarser than that in a lower container in a region where the source material consisted entirely of much finer sediment.

The one exception to the obvious decrease in grain size with increasing height occurred at the Bristol site where the sediment in the upper container was slightly coarser than that in the lower container. Unless there were errors in analysis (and the analyses were double checked), the following explanation may well account for this anomaly. The material of sand size is very limited at Bristol, since the playa sediment consists mostly of clay and silt-size material and less than 10 percent of sand. One very strong storm could have moved sand of 0.20 mm at a sufficiently high elevation to place the sand in the upper trap as well as in the lower trap. Succeeding storms of lesser violence would have added little if anything to the upper trap but added sufficient fine material in the lower trap to reduce the median diameter of the sediment in that container.

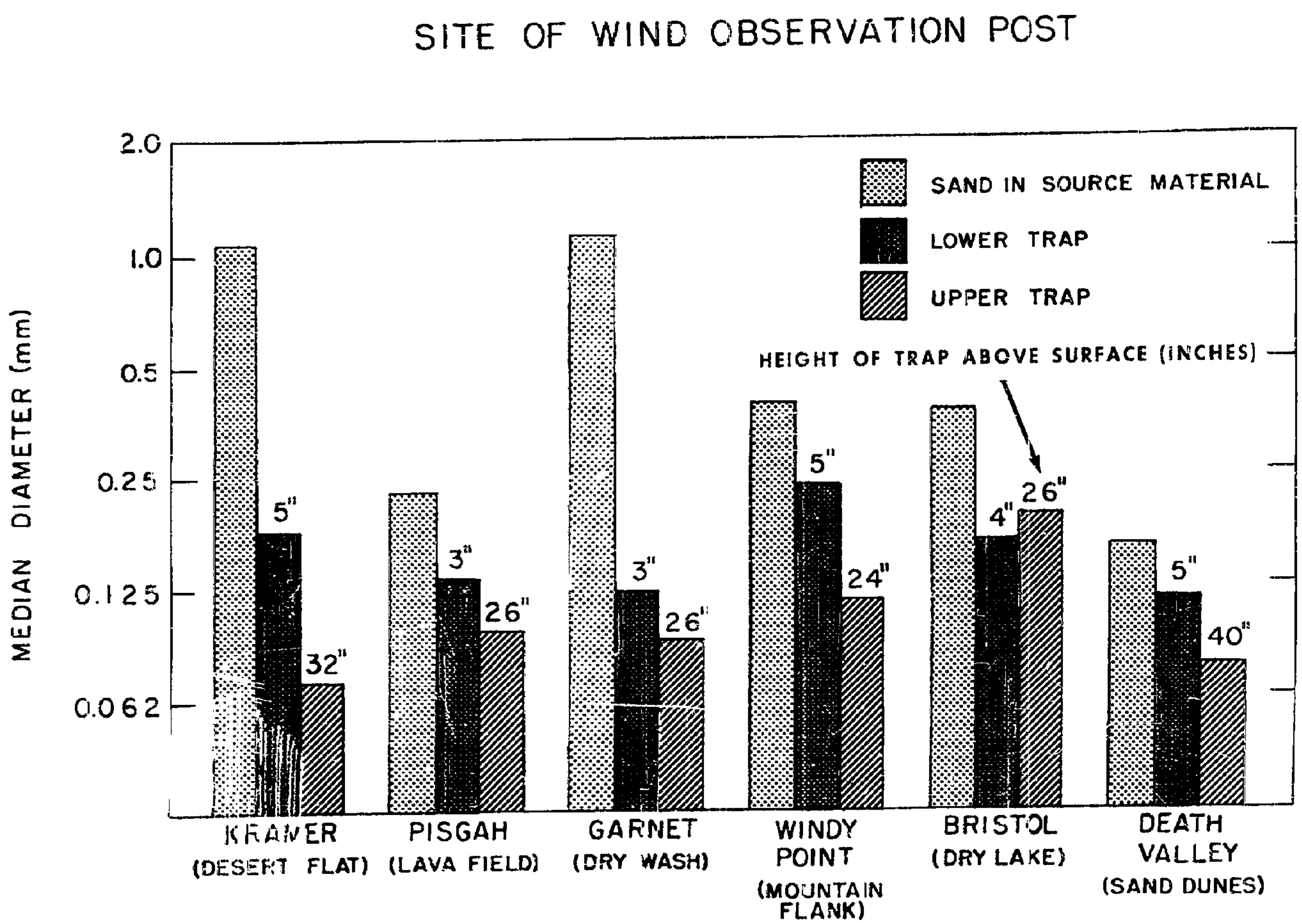

Figure 31. Median diameter of sediment in source area as compared to sediment trapped in upper and lower containers on observation posts.

This appears to be the case, since much more material was retained in the lower trap, and of this, a higher percentage was in the very fine size groups.

The overall variation of grain size with increasing height at the observation post traps is shown by the 6 histograms in Figure 32. The materials in the traps at the Death Valley dunes, Garnet, and Pisgah posts were analyzed and the weight percent of material in the standard-size groups was plotted against particle diameter in millimeters. At the Death Valley post the great increase with height in the weight percent of material between 0.125 and 0.062 mm (very fine sand) can be noted, with a corresponding decrease of sediment in the fine and medium sand groups. At Garnet, there was a nearly 20 percent increase of fine sand at the upper trap, with appreciable reductions in the medium sand class (between 0.5 and 1.0 mm). At the Pisgah post there was an increase of nearly 10 percent in the very fine sand group in the upper container and a decrease of approximately 13 percent in the coarser material of the 0.5 to 0.25 mm size group.

All the histograms show that the amount of material of the finest-size groups generally increases by 10 to 15 percent with an increase in height above the surface, while the amount of material in the coarsest size group is reduced as much as 10 percent. There is a proportionate reduction with height of material in the intermediate-size groups as well.

Amount of material. Calculations were made showing relative amounts of material trapped in the upper and lower containers as indicative of the transporting ability of surface winds with increasing height. In a collection made on 10 October 1953 at the Death Valley dunes there were 585.28 grams of material in the lower container and only 0.438 grams in the upper container. In this case roughly 0.1 percent of the total collected was trapped at the upper level and 99.9 percent at the lower level. Another collection of sediment at the traps of Death Valley on 6 December 1953 revealed that 99.91 percent of the material was transported close to the surface and only 0.09 percent at the higher level. The weight relationship of material transported at the 2 levels at other observation sites was similar. At the Pisgah post 92.1 percent of the material collected was in the lower can and 7.9 percent in the upper; at Kramer the relationship was 97.4 percent (lower) to 2.6 percent (upper).

b. Data from stationary objects

The best evidence of the vertical distribution of windborne sand can be seen from the abrasive effects on stationary objects. Fence poles and telephone poles subject to the erosive action of sand-carrying winds show the effects of the most intense sand blasting at elevations between 3 and 18 inches from the surface. Above 18 inches little

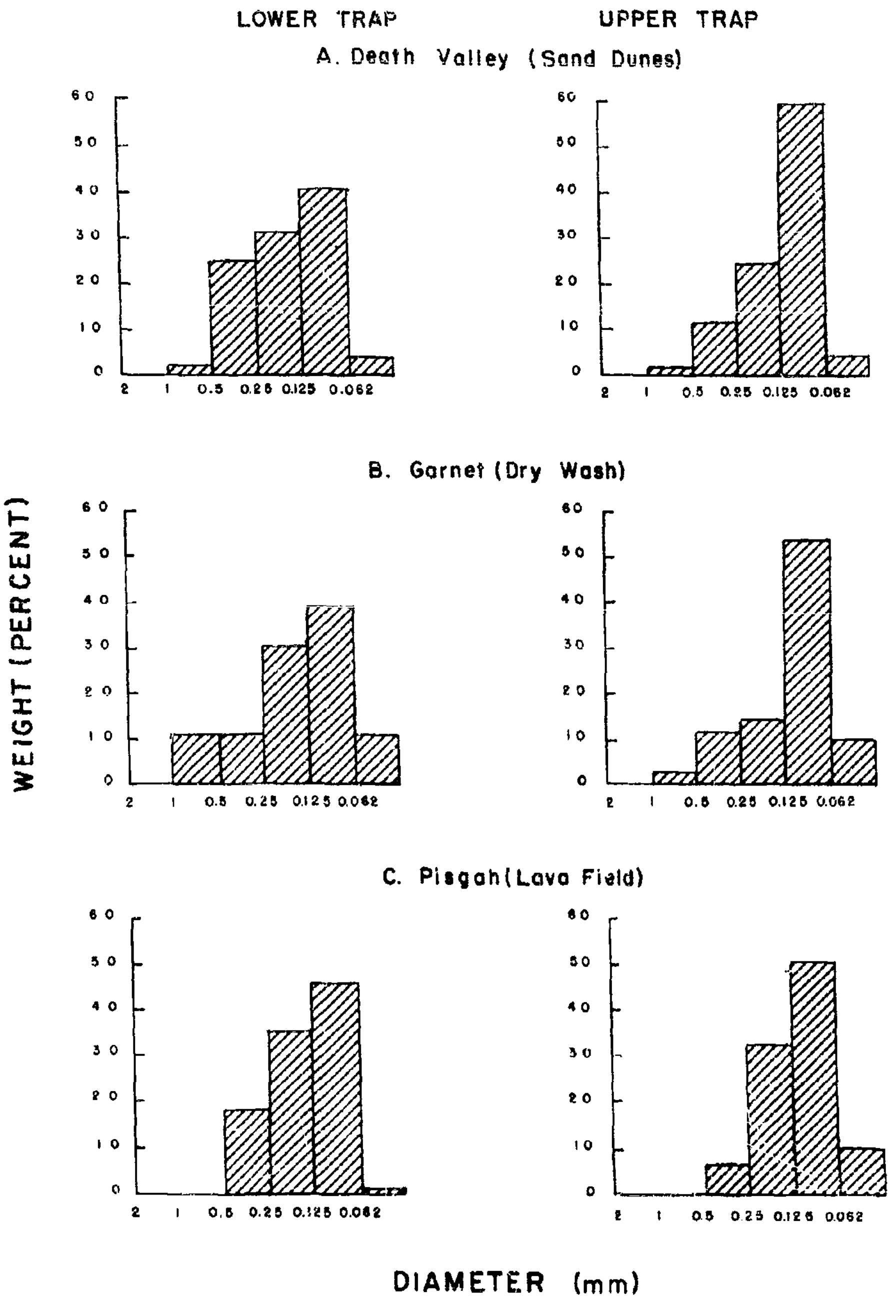

Figure 32. Histograms showing grain size variation with increasing height above the surface.

abrasion of the wood can be seen as a rule, although at Windy Point abrasive effects were noted up to 42 inches above the surface. In the Yuma dune area protection to a height of 24 inches (as shown in Fig. 33) has proved adequate to prevent abrasion. This is further evidence that the bulk of the material transported, and particularly that of sand size, is carried relatively close to the ground.

c. <u>Data from personal interviews and observations</u>

<u>Personal interviews</u>. One of the more spectacular illustrations of the variation in the abrasive power of sand-carrying winds at different heights was furnished by insurance companies. They reported instances of large trucks and trailers being severely sand-blasted up to heights of 3 or 4 feet with the upper portions of the cab and trailer unaffected. Some cases of severe abrasion to the lower portions of passenger cars were also reported. In all cases the vehicles exhibited a nearly perfect line where the sand-blasting effect ceased, leaving the uppermost portions unaffected.

<u>Personal observations</u>. During sand storms encountered in the course of the field investigations it was repeatedly noted that the coarse material was carried almost entirely near the surface and only material of dust size was carried to greater heights. Usually the wind-driven sand moved as a definite sheet or layer that ended abruptly 1 or 2 feet above the surface.

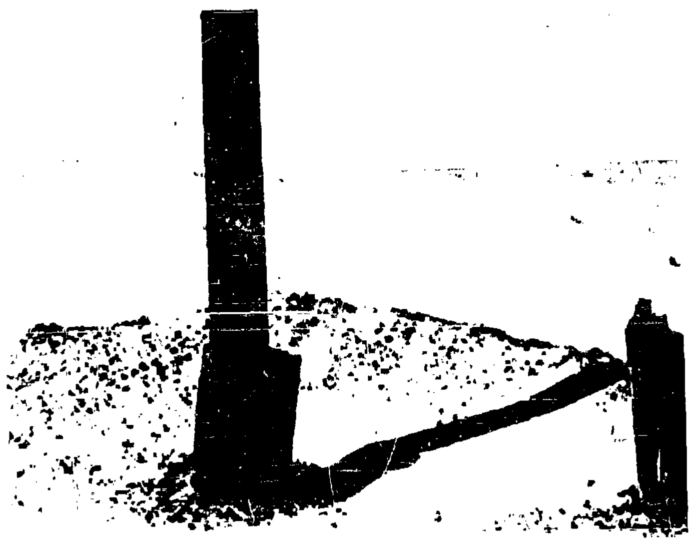

Figure 33. Short length of pipe used to protect base of post in Yuma dunes area suggests that most abrasion occurs close to ground. Note intense abrasion of older stump.

Bagnold called it "a moving carpet." During the wind storm of 4 December 1953 in Death Valley, the wind blowing down the valley from the northwest (Fig. 34) raised clouds of dust that completely hid the Cottonwood Mountains on the west from the road on the east side of the valley. It was calculated that the dust cloud had a minimum height of 1,500 feet, yet the main movement of sand was within 6 feet of the surface and mostly within the first 2 feet (Fig. 35).

4. Conclusions regarding abrasion on specified surface types

From data obtained at the observation posts and from personal observations of wind abrasion on natural objects and equipment taken into the desert by man, the following conclusions can be drawn.

a. The areas of most effective wind abrasion are active sand dunes, tracts along large dry washes, and certain exceptional areas such as a mountain notch where wind is funnelled through a gap. In all these situations there must be: an abundant source of incoherent sand, strong winds, no surface crusts, and little binding action by vegetation. Such areas are unstable from a geologic standpoint, since they are not in equilibrium with their environment.

b. Dry playa surfaces, wet playa surfaces (salt flats), lava flows, cinder fields, desert pavements, and desert flats are areas of little wind abrasion. The dry playa and salt flat surfaces are well protected by a surface crust of clay, salt, or a mixture of the two, in which material normally available for wind transport is held in place by a natural binder. In the lava and cinder areas there is available little loose material small enough to be carried by the wind, and the rough, irregular surface breaks up the flow of wind across the surface. In regions of desert pavement the surface is protected by a layer of coarse lag gravel, the finer material long since having been removed. At Garnet, previous removal of fine material by the wind has left only very coarse sand and granules at the surface. Only exceptional winds can transport this material. The surface of the desert flat is apparently in equilibrium, and only unusually strong winds disturb the surface.

None of the areas that are in a state of equilibrium with their indiv[illegible] .s a zone of effective wind abrasion unless [illegible] disturbed by vehicles, cultivation, or new sedimenta[illegible] by geologic agents, such as floods.

Figure 34. Windstorm of 4 December 1953 raises clouds of dust in northern part of Death Valley.

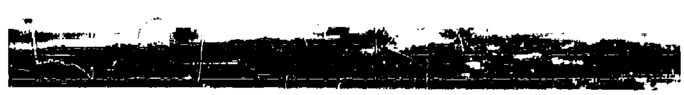

Figure 35. Sand drifts along close to surface while dust rises so high as to obscure 6,000-feet-high mountains across valley. Death Valley windstorm, 4 December 1953.

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3. Wind
4. Desert tests
5. Storms
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U. S. Army Natick Laboratories, Natick, Mass. A STUDY OF WINDBORNE SAND AND DUST IN DESERT AREAS by Thomas Clements, John F. Mann, Jr., Richard O. Stone and James L. Eymann. Aug 1963 69 pp illus (Technical Report ES-8)

Severe sand and dust storms occur at a rate of less than 2 per year on the average in the desert areas of southwestern United States. Less severe storms average about 4 per year. Most storms occur in late winter or spring and last for a period of 1 to 3 days. Storm incidence is higher in desert areas that have been disturbed by man's activities, such as agriculture or large-scale military maneuvers. During a storm, sand and dust in militarily significant amounts are carried a few miles at most, but generally only a few hundreds or thousands of feet. Wind-driven sand is carried mostly within 2 feet of the ground, with 6 feet as a maximum height in all but extremely high winds.

Critical pick-up velocities of winds vary according to the type of desert surface, the grain size and coherency of the surface materials, and whether or not the surface has been disturbed artificially. In dune areas, winds of 10 to 15 miles per hour will initiate movement, and on other sandy terrain, winds of 20 miles per hour will be necessary for this. Fine materials on desert flats will be set in motion at 20 to 25 miles per hour, and on alluvial fans and playas at 30 to 35 miles per hour. No wind-blown material will be derived from desert pavements unless the surface has been broken, and on all other above-mentioned types, disturbing the surface will lower critical pick-up velocities by as much as 5 miles per hour.

1. Dust storms
2. Sand
3. Wind
4. Desert tests
5. Storms
6. Gusts

I. Clements, Thomas
II. Mann, John F., Jr.
III. Stone, Richard O.
IV. Eymann, James L.
V. Title
VI. Series

UNCLASSIFIED

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